GEOLOGY

Deep-Water Sedimentary Structures
Pliocene Pico Formation, Santa Paula Creek
Ventura Basin, California

CALIFORNIA DIVISION OF
MINES AND GEOLOGY
SPECIAL REPORT 89

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DEEP-WATER SEDIMENTARY STRUCTURES
PLIOCENE PICO FORMATION
SANTA PAULA CREEK, VENTURA BASIN
CALIFORNIA

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Special Report 89
California Division of Mines and Geology
Ferry Building, San Francisco, 1966

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SPECIAL REPORT 89

Price $1.50

CONTENTS

Page

Abstract 5

Introduction 7

Geologic setting and environment of deposition 7

General features 12

Sedimentary structures 12

Stratification 12

Graded bedding 18

Small-scale cross-stratification 18

Convolute lamination 21

Sole marks 23

Disturbed bedding 24

Fossils with preferred orientation 30

Directional measurements 31

Summary and discussion 32

Conclusions 38

References cited 39

Illustrations

Figure 1. Location and geologic maps, Santa Paula Creek locality 6

Figure 2. Photo showing Santa Paula Creek locality 8

Figure 3. Measured stratigraphic section at Santa Paula Creek, lower part 10

Figure 4. Measured stratigraphic section at Santa Paula Creek, upper part 11

Figure 5. Detailed columnar section of beds between 43 and 45.8 m 14

Figure 6. Log-probability plot of bedding thicknesses between 43 and 45.8 m, showing approximately a log-normal distribution 15

Figure 7. Photo of ruptured mudstone layer 16

Figure 8. Photo showing small-scale cross-stratification and contorted stratification near 43 m 19

Figure 9. Sketch of bed with convolute lamination at 45.5 m 20

Figure 10. Photo showing convolute lamination and cross stratification at 45.5 m 20

Figure 11. Relation between thickness and wave length of convolute lamination 21

Figure 12. Sections of bed with convolute lamination at 45.5 m 22

Figure 13. Sketch of bed at 50.6 m 23

Figure 14. Photo showing grooves on upper surface of mudstone layer near 50 m 24

Figure 15. Photo showing intestiniform layer at 48.6 m 25

Figure 16. Sketches of sedimentary structures, I. A: Deformation of interbedded sandstone and mudstone; B: Flame structures at base of massive sandstone; C: Load pockets 26

Figure 17. Sketches of sedimentary structures, II. A: Scour channel at base of laminated pebbly sandstone; B: Overfold of mudstone at base of massive coarse-grained sandstone; C: Layer of pebbles along bedding plane. D: Imbricated shells; E: Shells, concave down; F: Imbricated mudstone slabs 27

Figure 18. Current senses from small-scale cross-stratification 29

Figure 19. Orientations of varieties of contorted stratification 30

Figure 20. Orientations of grooves, ripple marks, flame structures, and imbricated clasts 31

ABSTRACT

The middle part of the Pico Formation (Pliocene), according to interpretations of foraminiferal and molluscan ecology and paleogeographic reconstructions, was deposited in marine waters at least 270 meters deep. The ideal exposures of the beds at Santa Paula Creek provide an unusual opportunity to examine sedimentary structures in detail, presumably the result of turbidity currents, in order to reconstruct the mechanics of sedimentation. Among the structures are: stratification with both erosional and deformational contacts, internal stratification and lamination, graded bedding, small-scale cross-stratification, convolute lamination, sole marks, contorted stratification, disturbed bedding, fossils with preferred orientation, scour channels, imbricated clasts and shells, ripple marks, flame structures, pull-aparts, load pockets and waves, and many others. Ideal graded bedding is uncommon and most sandstone layers display grading superposed upon other structures, such as internal lamination.

Thin and persistent sandstone and mudstone layers, with intricate and characteristic sedimentary structures across the full width of exposure, imply sedimentary infilling on a nearly flat sea floor. Units consisting of laminated sandstone at the base and cross-stratified finer sandstone above, with other structures, indicate bottom-seeking currents which tend to level the sedimentary surface. Deformational and erosional contacts at the base of such layers (including scours, flames, overfolds, pullaparts, and load pockets and waves) suggest vigorous current impact and drag. In fact, deformed and disturbed beds, even including those contorted to intestiniform masses, may be the result of such current drag rather than the downslope movement by slumping under gravity. This interpretation is also supported by the association of thicker and coarser sandstone layers with disturbed beds. Folds of disturbed beds are considered as far less reliable indicators of paleoslope than primary sedimentary structures such as small-scale cross-stratification. At Santa Paula Creek the latter indicate flow of current primarily to the west, with great variability, but contributing to the longitudinal infilling of the trough. Dark mudstone layers apparently were also laid down by bottom-seeking currents, but reddish-weathering mudstone layers accumulated from pelagic detritus deposited as gentle "rain" largely from overflows or interflows above.

A broad and nearly level trough with steep margins rising to an irregular shoreline with an approximately east-west trend, emerges from this re-study as the paleogeographic picture. Sediment—sand and mud with some gravel—moved downslope within underflows that acquired their energy in flowing down the trough margin. Much of the debris probably debouched from submarine canyons, perhaps in a rush but also intermittently and continuously for longer periods. The underflows apparently possessed great complexity, weaving from side to side, with variable turbulence in three directions and sufficient energy to move a bed load by traction. Stronger currents vigorously eroded and disturbed the sea floor. Nice adjustment between turbulence, traction, the frictional resistance of the sea floor, character of the sediments, and other factors, is implied by the sedimentary structures now on view as stilled-stages in this emplacement process. Characteristics of the substrate, such as thixotropy, dilatancy, and compaction history, also regulated the resulting sedimentary structures.

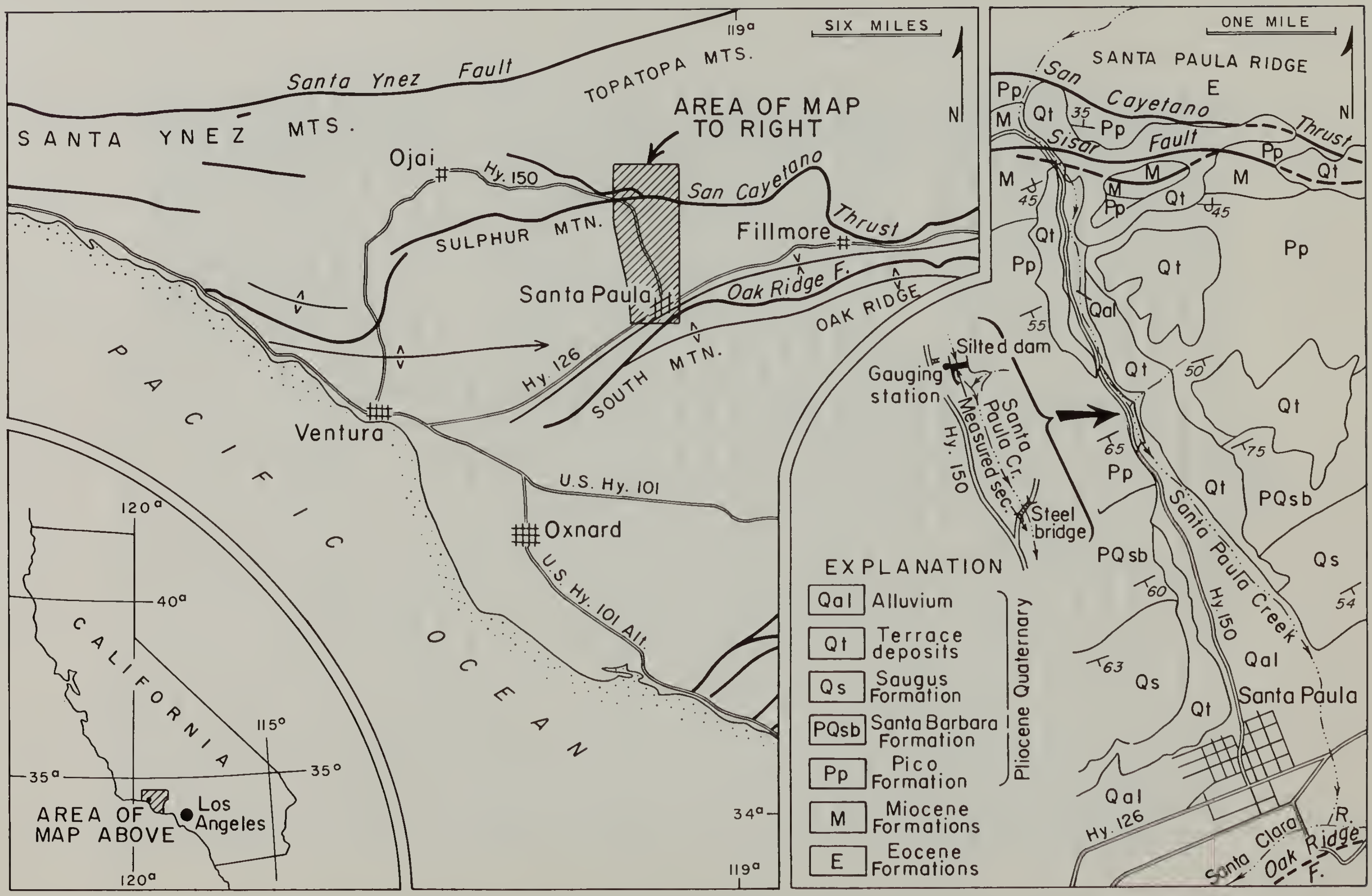

Figure 1. Location and geologic maps, Santa Paula Creek locality. Data simplified from Bailey (1954, Map Sheet 4) and Jennings and Traxel (1954, Map 10, p. 31).

DEEP-WATER SEDIMENTARY STRUCTURES, PLIOCENE PICO FORMATION, SANTA PAULA CREEK, VENTURA BASIN, CALIFORNIA[1]

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INTRODUCTION

The exposures of marine Pliocene beds along Santa Paula Creek have acquired nearly classic status in the study of turbidity-current deposits. They were first described by Natland and Kuenen (1951) and many ideas concerning turbidity currents were based upon interpretations of these rocks. Here reasons are compelling for deposition in a calm and relatively deep basin—the environment deemed most likely for deposition by turbidity currents. Data from foraminiferal ecology and geologic relations require, for example, that the depth of water was greater than 270 m (900 ft.) during sedimentation. The purpose of the present paper, therefore, is to describe these rocks in more detail, giving special emphasis to features that lead to interpretations concerning the manner of deposition.

This re-study has been limited to field examination of about 225 m of section, typical of the Pico Formation, Ventura basin, California. Winter floods of 1962 cut deeply into the beds and for the first time in several years exposures were clean and continuous. As the strata are relatively soft, they can be dissected in the field with a knife or trowel in order to expose the three-dimensional form of the structures and increase confidence in observations.

Geologic Setting and Environment of Deposition

The beds at Santa Paula Creek (referred to by Natland and Kuenen in 1951, fig. 1, as Locality 5) lie near the thickest part of the Plio-Pleistocene succession in Ventura basin (figures 1 and 2). About 5200 m (17,000 ft.) of sediments are present in this region of which approximately 3600 m (12,000 ft.) are Pliocene (Jennings and Troxel, 1954, p. 32). The strata described are in the midst of this section, and are assigned to the middle part of the Pico Formation. Here the beds dip southward at about 70 degrees and form part of the northern flank of the Ventura syncline between the north-dipping San Cayetano fault on the north, and the south-dipping Oak Ridge fault on the south. A structure section depicting these relations, as well as a description of regional geology, is given by Bailey (1954).

Estimates of depth of water at time of sedimentation are based on three approaches: (1) interpretations from foraminiferal and molluscan ecology, (2) reconstructions of the regional paleogeography, and (3) analogies with offshore topography bordering southern California today. Data from Foraminifera have proved most useful in view of the abundance of species in Pliocene strata still alive in modern oceans. Under the assumption that the tolerance of benthonic species for temperature and depth has not changed signifi-

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[1] Manuscript received June 22, 1964.

[2] Department of Geology, University of California, Los Angeles. This paper is the outgrowth of work in a graduate class entitled *Field Investigations in Geology* (Geology 259) conducted during the spring semester of 1962.

The writers are grateful to H. E. Clifton, K. J. Hsu, and E. L. Winterer for critical comments on the manuscript, to Mrs. Opal M. Kurtz for drafting, and to C. A. Hall, Jr., for identifying pelecypods.

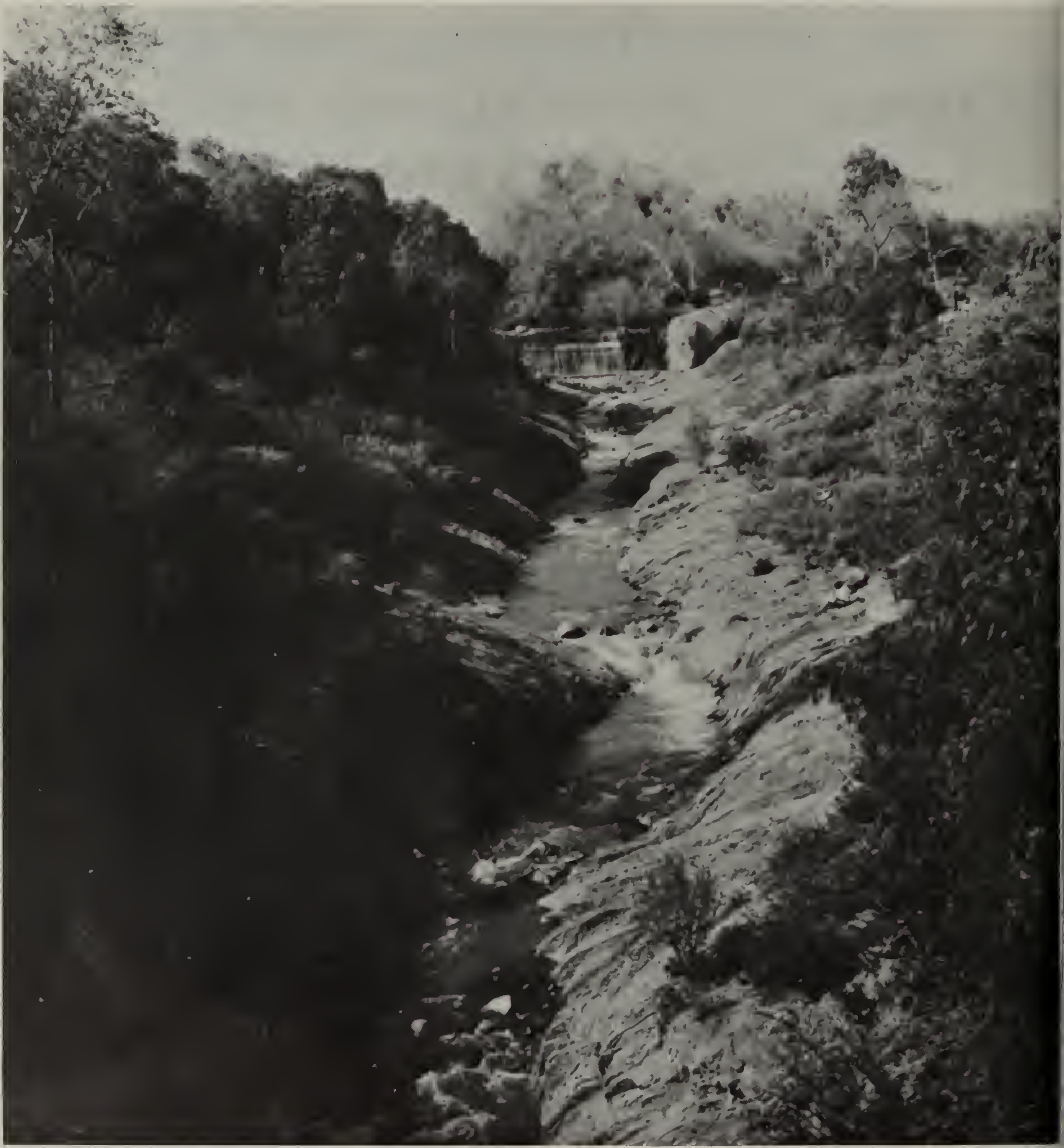


Figure 2. View of Santa Paula Creek locality, to the northwest, April 1962.

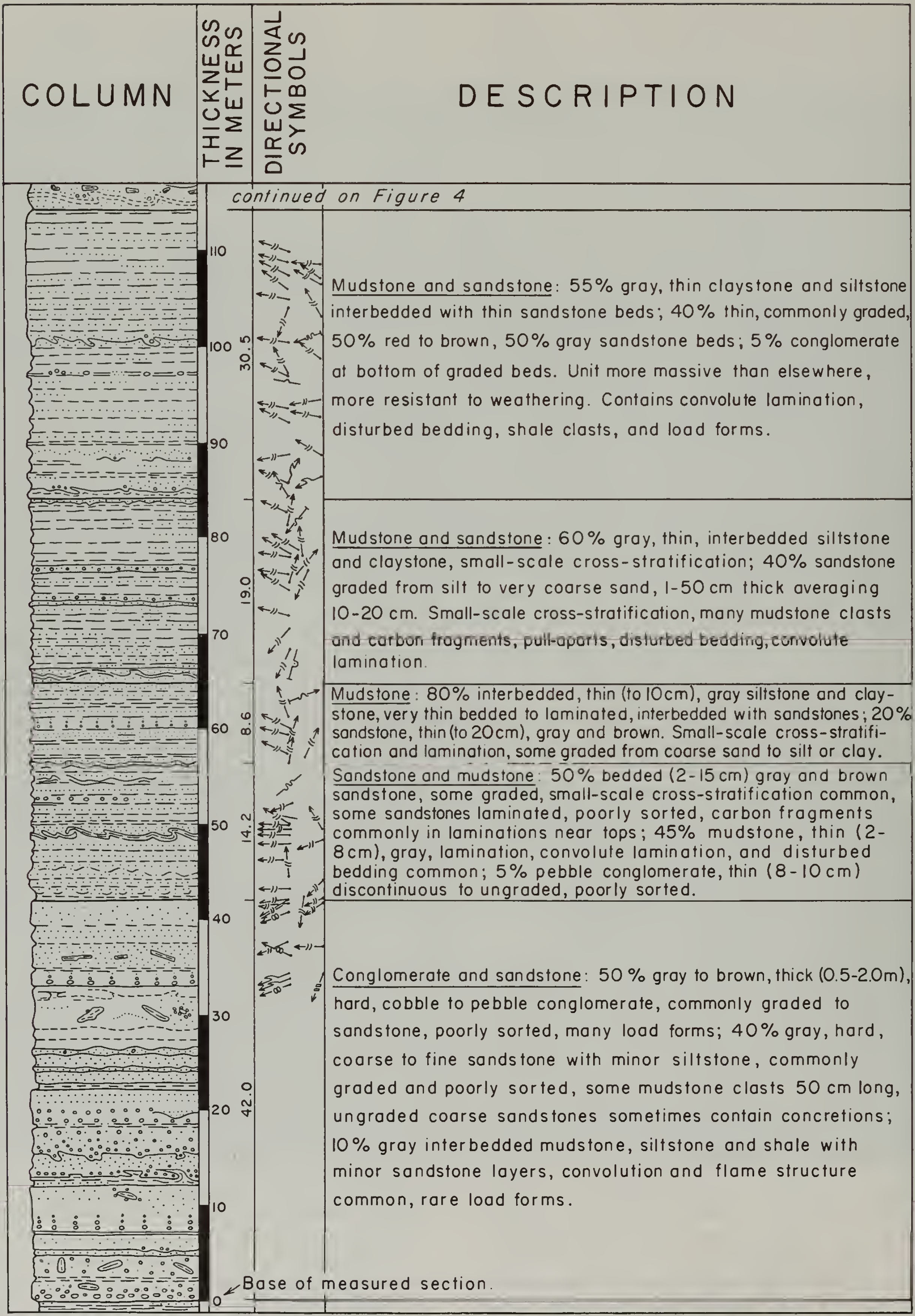
cantly with time, conclusions may be drawn concerning water depths in the Pliocene since we can observe the environments where the faunas live today. Natland, in particular, has utilized this approach (1933, 1957), followed by Crouch (1952), Bandy (1953), Winterer and Durham (1962, p. 306–308), and others. Studies of mollusks (Woodring, 1938; Winterer and Durham, 1962) tend to confirm the depth interpretations based on Foraminifera. Until isotopic studies utilizing O_{18} have been applied to these Pliocene faunas, depths interpreted by such comparisons seem to be the most helpful.

Using this approach, Natland concluded that the depth of water at the Santa Paula Creek locality was between 600 and 1200 m (2,000–4,000 ft.) (Natland and Kuenen, 1951, p. 84). More recently (1957, p. 556) he has revised his estimate to 270 to 600 m (900–2,000 ft.) which corresponds to depth zone T_4 of Crouch (1952, p. 809) and the northern upper bathyal zone of Bandy (1953, p. 172). The temperature range for these depths is between 5 and 8.5°C and all three investigators conclude that temperature is the ecologic factor of primary significance; variations in salinity, oxygen content, and other factors are of comparatively minor importance. The minimum-depth figure of 270 m (900 ft.) probably arises from the practice of subdividing modern oceanic environments into contiguous depth zones such as littoral, neritic, bathyal, and abyssal (Sverdrup and others, 1942, figure 67; Kuenen, 1950, figure 138; Hedgpeth, 1957, figure 1; Cloud, 1961, figure 3), and then assigning faunal assemblages to these zones. Investigations of microfaunal distribution have not been further refined and the depth indicated by the fauna at Santa Paula Creek is best referred to as upper bathyal, although it may be well down in this depth zone.

It is not desirable to attempt greater precision because of the assumptions underlying this method of determining depths in the geologic past. Temperatures of oceanic bottom waters can be no colder than those formed at the surface of polar seas and during the Tertiary, very cold waters were not generated in polar regions (Emiliani, 1954; Bruun, 1957, p. 668). Hence, temperature gradients in the Pliocene sea bordering southern California were probably less steep than at present. Furthermore, abyssal benthonic faunas today, now living in waters near 0°C, are quite similar to those preserved in early Tertiary strata deposited in warmer waters. These faunas, therefore, may have acquired a tolerance for colder temperatures with the passage of time. Moreover, certain species clearly show changes in temperature tolerance with time (Winterer and Durham, 1962, p. 306), so we can not always assume that the same species have immutable tolerances for temperature and depth. Nevertheless, these effects are not likely to change significantly most ecologic interpretations involving mid-Pliocene forms —those of interest in the present study—because of their relatively recent age. In fact, if the temperature gradients in Pliocene seas were less steep than at present, the depths arrived at by comparison with living habitats would be greater, but probably not significantly so.

The interpretation that the depth of water during sedimentation was bathyal is strengthened by considerations of regional geology. In the eastern part of the Ventura basin, for example, Winterer and Durham (1962) show that the Pliocene sea was about 600 m (2,000 ft.) deep. In addition to using paleoecology they traced near-shore beds through facies changes into distant beds which must have been downslope in deeper water. A similar approach, but over a shorter distance, was used earlier by Bailey (1935; see also Natland and Kuenen, 1951, p. 92) in strata transitional between Pliocene and Pleistocene and only a few miles from Santa Paula Creek. These studies, and others, suggest that the sea bottom sloped steeply basinwards for several miles, and then flattened at the basin floor. As the details of paleogeography are fitted together it seems likely that the submarine topography during the Pliocene was very much like that offshore at present, where deep basins receive sediment from shore, with coarser material passing primarily through submarine canyons. These modern basins are characterized by steep marginal slopes which are fairly irregular in plan, and with deep and nearly flat or very gently sloping floors (Emery, 1960, p. 50). The floors of near-shore basins receive sediment in three ways: first, by the settling of organic and chemical debris at an approximately uniform rate over the whole basin; second, by the settling of detritus from plumes of fresh water extending seaward from land streams as overflows, by diffusion outward from land, and by wind transport; and third, by turbidity currents. Slopes are less than 0.3° where the first two processes predominate and seldom exceed 2.0° where the effects of turbidity currents mask the other two. These basin floors are beyond doubt regions of sediment infilling and possess a relatively smooth upper surface never very far from equilibrium. Small depressions and channels are soon filled.

From these considerations we conclude that sedimentation at Santa Paula Creek took place in upper bathyal waters within a few miles, probably not more than 10, from a coast on the north. Inasmuch as Pliocene sedimentary and structural trends are roughly east-west in this region the coast no doubt had a similar trend, which, like the present-day Santa Barbara



Mudstone and sandstone: 55% gray, thin claystone and siltstone interbedded with thin sandstone beds; 40% thin, commonly graded, 50% red to brown, 50% gray sandstone beds; 5% conglomerate at bottom of graded beds. Unit more massive than elsewhere, more resistant to weathering. Contains convolute lamination, disturbed bedding, shale clasts, and load forms.

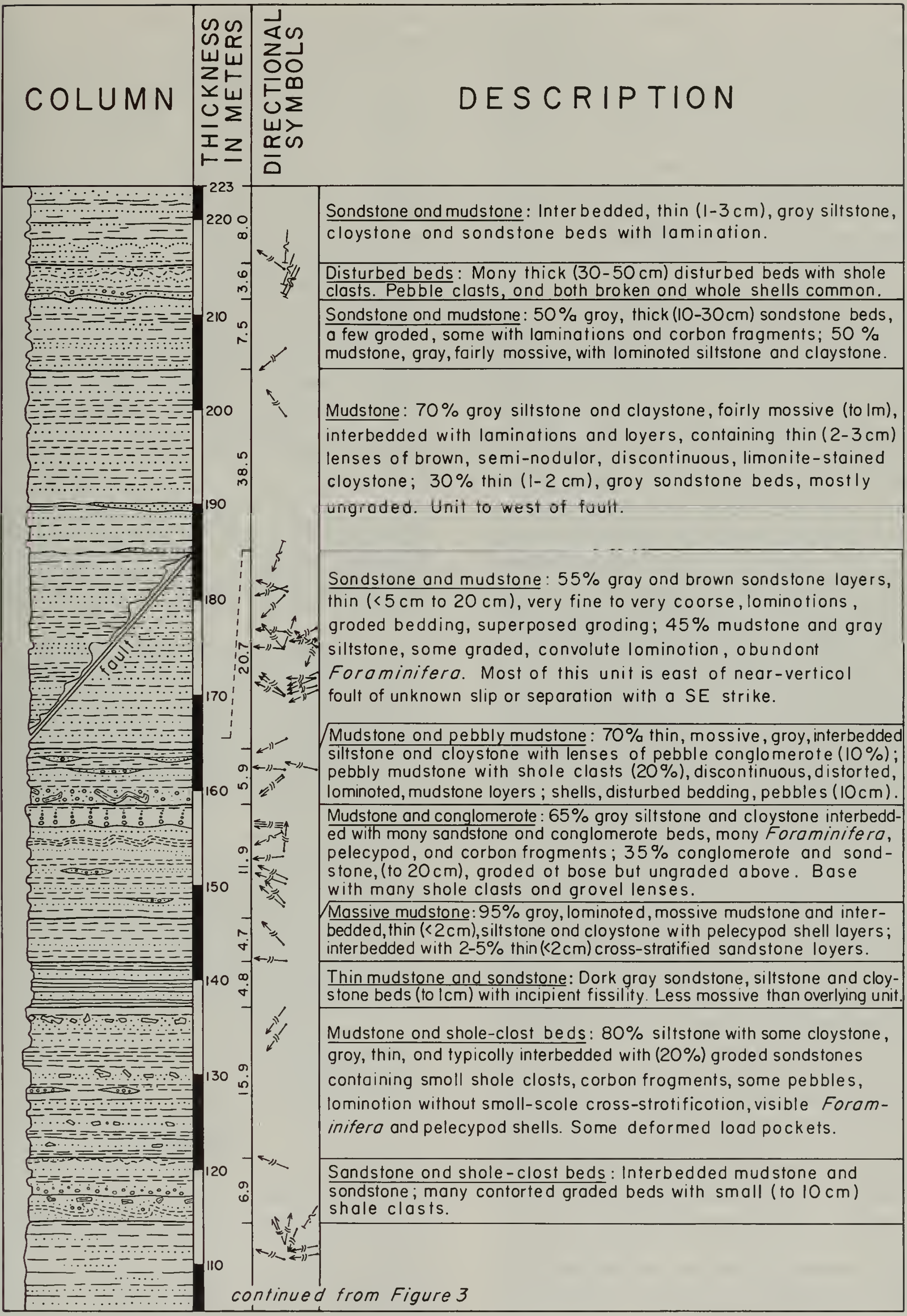
Mudstone and sandstone: 60% gray, thin, interbedded siltstone and claystone, small-scale cross-stratification; 40% sandstone graded from silt to very coarse sand, 1-50 cm thick averaging 10-20 cm. Small-scale cross-stratification, many mudstone clasts and carbon fragments, pull-aparts, disturbed bedding, convolute lamination.

Mudstone: 80% interbedded, thin (to 10cm), gray siltstone and claystone, very thin bedded to laminated, interbedded with sandstones; 20% sandstone, thin (to 20cm), gray and brown. Small-scale cross-stratification and lamination, some graded from coarse sand to silt or clay.

Sandstone and mudstone: 50% bedded (2-15 cm) gray and brown sandstone, some graded, small-scale cross-stratification common, some sandstones laminated, poorly sorted, carbon fragments commonly in laminations near tops; 45% mudstone, thin (2-8 cm), gray, lamination, convolute lamination, and disturbed bedding common; 5% pebble conglomerate, thin (8-10 cm) discontinuous to ungraded, poorly sorted.

Conglomerate and sandstone: 50% gray to brown, thick (0.5-2.0m), hard, cobble to pebble conglomerate, commonly graded to sandstone, poorly sorted, many load forms; 40% gray, hard, coarse to fine sandstone with minor siltstone, commonly graded and poorly sorted, some mudstone clasts 50 cm long, ungraded coarse sandstones sometimes contain concretions; 10% gray interbedded mudstone, siltstone and shale with minor sandstone layers, convolution and flame structure common, rare load forms.

Figure 3. Measured stratigraphic section at Santa Paula Creek, lower part. Observations in this study are keyed to this measured section and its continuation in figure 4. Refer to Table 3 for symbols.



Sandstone and mudstone: Interbedded, thin (1-3 cm), gray siltstone, claystone and sandstone beds with lamination.

Disturbed beds: Many thick (30-50 cm) disturbed beds with shale clasts. Pebble clasts, and both broken and whole shells common.

Sandstone and mudstone: 50% gray, thick (10-30cm) sandstone beds, a few graded, some with laminations and carbon fragments; 50% mudstone, gray, fairly massive, with laminated siltstone and claystone.

Mudstone: 70% gray siltstone and claystone, fairly massive (to 1m), interbedded with laminations and layers, containing thin (2-3cm) lenses of brown, semi-nodular, discontinuous, limonite-stained claystone; 30% thin (1-2 cm), gray sandstone beds, mostly ungraded. Unit to west of fault.

Sandstone and mudstone: 55% gray and brown sandstone layers, thin (<5 cm to 20 cm), very fine to very coarse, laminations, graded bedding, superposed grading; 45% mudstone and gray siltstone, some graded, convolute lamination, abundant *Foraminifera*. Most of this unit is east of near-vertical fault of unknown slip or separation with a SE strike.

Mudstone and pebbly mudstone: 70% thin, massive, gray, interbedded siltstone and claystone with lenses of pebble conglomerate (10%); pebbly mudstone with shale clasts (20%), discontinuous, distorted, laminated, mudstone layers; shells, disturbed bedding, pebbles (10cm).

Mudstone and conglomerate: 65% gray siltstone and claystone interbedded with many sandstone and conglomerate beds, many *Foraminifera*, pelecypod, and carbon fragments; 35% conglomerate and sandstone, (to 20cm), graded at base but ungraded above. Base with many shale clasts and gravel lenses.

Massive mudstone: 95% gray, laminated, massive mudstone and interbedded, thin (<2cm), siltstone and claystone with pelecypod shell layers; interbedded with 2-5% thin (<2cm) cross-stratified sandstone layers.

Thin mudstone and sandstone: Dark gray sandstone, siltstone and claystone beds (to 1cm) with incipient fissility. Less massive than overlying unit.

Mudstone and shale-clast beds: 80% siltstone with some claystone, gray, thin, and typically interbedded with (20%) graded sandstones containing small shale clasts, carbon fragments, some pebbles, lamination without small-scale cross-stratification, visible *Foraminifera* and pelecypod shells. Some deformed load pockets.

Sandstone and shale-clast beds: Interbedded mudstone and sandstone; many contorted graded beds with small (to 10 cm) shale clasts.

continued from Figure 3

Figure 4. Measured stratigraphic section at Santa Paula Creek, upper part.

coastline, protected the trough from powerful swell originating from great storms in the north Pacific Ocean. Waters deeper than a few hundred feet and beyond a mile or so from headlands or constrictions between islands, must have been essentially devoid of tidal, longshore, and major circulation currents of sufficient competence to transport sand-sized sediment. The bottom environment of the Santa Paula Creek locality during the Pliocene was accordingly one of still water, and it was into this calm environment that sedimentation took place.

GENERAL FEATURES

The stratigraphic section studied (figures 3, 4) consists primarily of interbedded sandstone, mudstone, and siltstone with some beds of conglomeratic sandstone and pebbly mudstone. The sandstones are mainly arkosic wackes (Williams and others, 1954, p. 289) and contain more than 10 percent mud as matrix. A few fine sandstone layers, however, are arenites since they are better sorted and contain little if any mud. The base of the section is marked by a series of conglomeratic sandstones aggregating about 42 m in thickness. These units, which crop out as resistant layers near a dam are irregularly bedded. Some beds here display large load pockets, flame structures, overfolds, pull-aparts, and scours (figures 16B and C, 17A and B). Other beds contain slabs of mudstone up to 1 m in length, but averaging between 10 and 30 cm, which are torn and bent, or are imbricated (figure 17F). The distorted mudstone slabs and chips are identical in lithology to mudstones of the Pico Formation immediately underlying, and no doubt have been derived from these strata. Granules and megaclasts up to 20 cm in diameter occur dispersed, but usually in lenses and pockets within the sandstone beds. These larger clasts consist primarily of rounded and subrounded, gray medium-grained sandstone (probably derived from Eocene strata exposed to the north) and purple, gray, and buff porphyritic metavolcanics (probably redeposited from older conglomerates). A few subrounded pebbles of buff siliceous shale may have been derived from the Monterey formation (middle Miocene).

The stratigraphic section above the conglomeratic sandstone beds consists of interbedded sandstone and mudstone. On the whole this sequence is monotonous, although in detail there are variations, some of which are repetitive, or even cyclic. Most of the sandstone layers are fine- to medium-grained wackes, and many display small-scale cross-stratification. Interbedded dark brown mudstone, siltstone, and claystone are in general faintly laminated, but locally are massive in units several centimeters thick. True fissility was not noticed and only rarely is lamination developed sufficiently to warrant use of the term "shale." Mudstone is commonly more resistant to weathering than friable sandstone, although it flakes easily upon desiccation. Minor lithologic types are conglomerate and pebbly mudstone, one bed of which has been described elsewhere (Crowell, 1957, p. 998). Conglomerate is found in discontinuous layers and lenses interbedded with sandstone and mudstone, and only rarely exceeds 10 cm in thickness. Large clasts in these beds consist of the same lithologic types as in the conglomeratic sandstones at the base of the section studied.

Organic remains are common throughout the section. Most layers of dark mudstone are flecked with conspicuous *Foraminifera* and thin-shelled mollusks, chiefly *Macoma* (?) sp. and *Semele* (?) sp., which occur in layers or as broken fragments mixed with conglomerate and pebbly mudstone. Charcoal or carbonized fragments of seaweed are abundant in the section, and at places layers up to several cm thick consist of woody and fibrous brown resinous material. In one layer a small pine cone and deer bone were recovered (Crowell, 1957, p. 999). Elsewhere small fragments of charcoal are dispersed within sandstone and are conspicuous on some bedding planes.

SEDIMENTARY STRUCTURES

One of the major purposes of the present study is to describe the many types of sedimentary structures in the Pico Formation at Santa Paula Creek. These structures, located in the measured section (figures 3, 4), are dealt with according to the following organization.

- Stratification
  - Bedding thickness and sequential arrangement
  - Lateral continuity of bedding
  - Contacts between beds
    - Erosional contacts
    - Deformational contacts and load structures
  - Internal stratification and lamination
- Graded bedding
- Small-scale cross-stratification
- Convolute lamination
- Sole marks
- Disturbed bedding
- Fossils with preferred orientation

Stratification

Although normal or parallel stratification is the mos obvious depositional structure of sedimentary rocks it is indeed surprising that it is seldom studied and discussed (Weller, 1960, p. 354). Perhaps this is because it is difficult to recognize those lithologic and structural components which impart a stratified appearance. Our discussion deals with those bedding ele

Table 1. Sandstone and Mudstone Bed Thicknesses Between 43 and 45.8 Meters, Pico Formation, Santa Paula Creek Measured Section.

Sandstone beds: (Total number, n, = 39) Mudstone beds: (Total number, n, = 59)

Class interval	Number /39	Percent	Cumulative percent	Class interval	Number /59	Percent	Cumulative percent
0.1-1	8/39	20.5	20.5	0.1-1	11/59	18.7	18.7
1.1-2	6/39	15.5	36.0	1.1-2	21/59	35.6	54.3
2.1-3	10/39	25.6	61.6	2.1-3	16/59	27.2	81.5
3.1-4	7/39	17.9	79.5	3.1-4	7/59	11.9	93.4
4.1-5	3/39	7.7	87.2	4.1-5	2/59	3.3	96.7
5.1-6	1/39	2.6	89.8	5.1-6	2/59	3.3	100.0
6.1-7	2/39	5.1	94.9	--	--	--	--
7.1-8	2/39	5.1	100.0	--	--	--	--
		100%				100%	

nents which when assembled yield the whole of stratiication. Our remarks apply mainly to detailed obserations although more distant views give an impression f remarkable evenness, continuity and parallelism of edding.

Bedding thickness and sequential arrangement. The trata studied at Santa Paula Creek are classed as thinnd very thin-bedded according to McKee and Weir 1953), except for the lower units of conglomeratic andstone. This latter sequence is approximately 42 m hick and contains several thick-bedded graded conlomeratic sandstones. For the section as a whole, the nean sandstone bed thickness is estimated as between and 10 cm, with an observed range from 0.1 to about 00 cm.

The statistical distribution of sandstone bedding hickness for 39 sandstone beds in 2.8 m of represenative section between 43.0 and 45.8 m is shown in igures 5 and 6 and in table 1. The distribution form of his small sample and of similar sequences elsewhere Bokman, 1953; Nederlof, 1959; McBride, 1962) sugest that the sandstone beds have an approximate logormal distribution. The distribution of 59 mudstone ayers in contact with the sandstone beds (figure 6) lso shows a good approximation to the log-normal istribution. The deviation from a straight line above 5 percent is probably the result of the small sample umber.

Thick sandstone beds at Santa Paula Creek are commonly coarser than thin ones, a relation noted in other reas by Kurk (1941 *in* Pettijohn, 1957, p. 161) and y Schwarzacher (1953). Beds containing fine pebbles, ranules or very coarse sand are usually greater than 5 cm in thickness, whereas beds composed of fine to very fine sand seldom exceed 6 cm in thickness. In general, therefore, thickness is proportional to the largest grains contained in the bed, although notable exceptions occur. For example, at many horizons in the section slabby clasts of mudstone, 20 cm in greatest dimension, occur in thin and very thin sandstone beds. Between 147 and 164 m, there are sandstone beds which overlie lenses of coarse conglomerate. These conglomerate lenses, which are bounded by planes of stratification and are composed of clasts up to 5 cm in length, are not more than 8 cm thick and 100 cm wide, and are beds that do not follow the expected relation between grain size and bed thickness. As shown in figure 17C, at places pebbles and cobbles are strewn along a bedding plane without intermediate size fractions.

The impression gained from examining the entire section is that similar sandstone-bed thicknesses tend to occur in groups, as in the 42 m thick-bedded sandstone and conglomerate at the base of the measured section, in the thin-bedded sandstone layers between 146.8 and 158.7 m, and in the very thin-bedded sandstones above an imbricated shell bed (43.0–45.8 m). A similar tendency for clustering was established statistically for Carboniferous strata in the Cantabrian Mountains of Spain by Nederlof (1959).

Mudstone, in contrast to sandstone, is almost everywhere very thin bedded with an average estimated thickness between 1 and 2 cm. The log-probability plot of the cumulative distribution of thickness of 59 mudstone beds (figure 6) is from beds overlying the imbricated-shell bed (43.0 to 45.8 m) but these data are probably representative of the entire section. Although most of the mudstone has a very thin-bedded

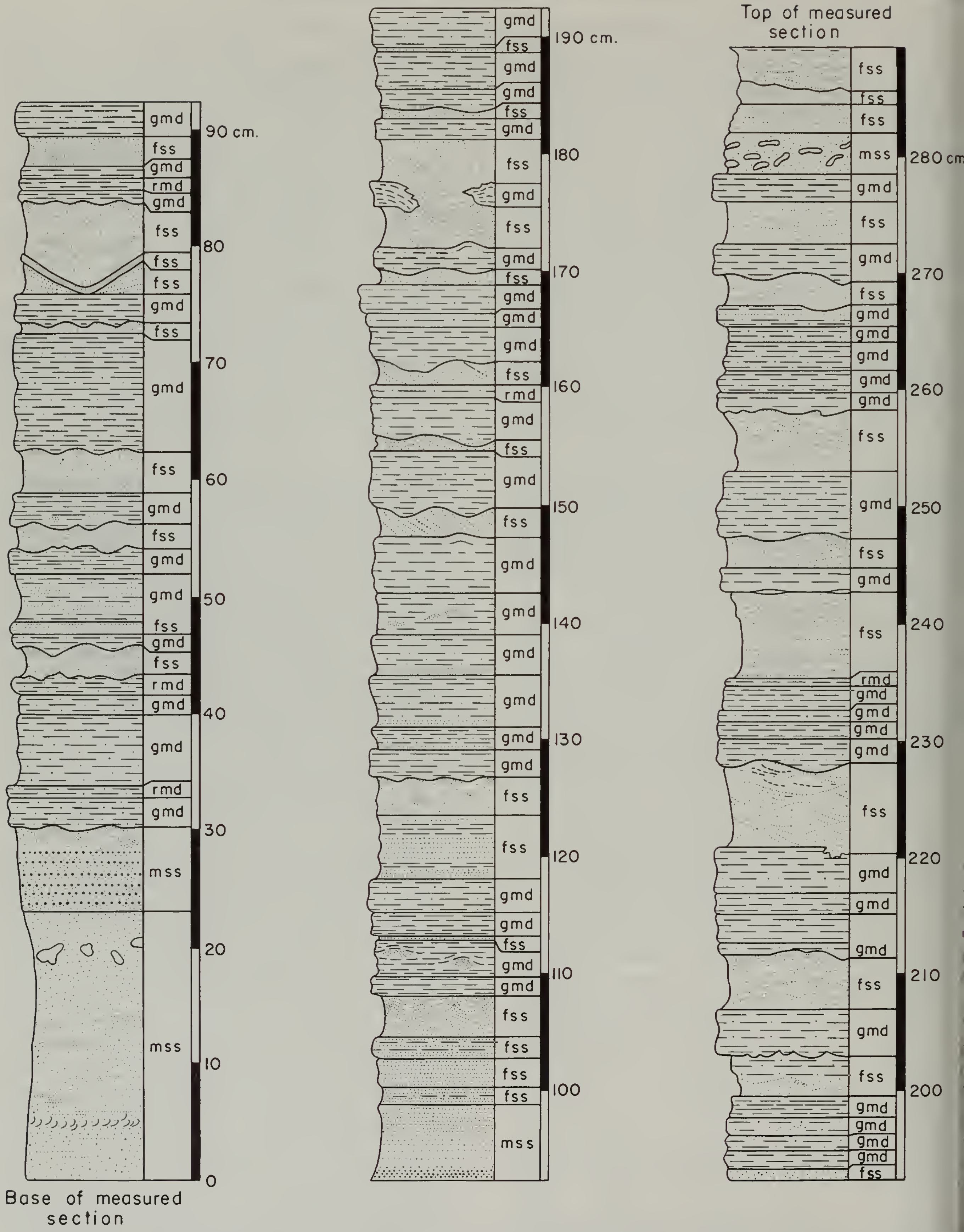


Figure 5. Detailed columnar section of 2.8 m of beds between 43 and 45.8 m. Generalized lithologies are: rmd, mudstone, brownish-gray weathering rusty-brown, minutely laminated, Foraminifera abundant; gmd, mudstone, gray and dark gray, commonly laminated, generally slightly coarse at base, Foraminifera present; fss, sandstone, gray to brown, fine grained with appreciable silt, carbonized plant fragments abundant; mss, sanc stone, gray weathering brown, medium to fine grained.

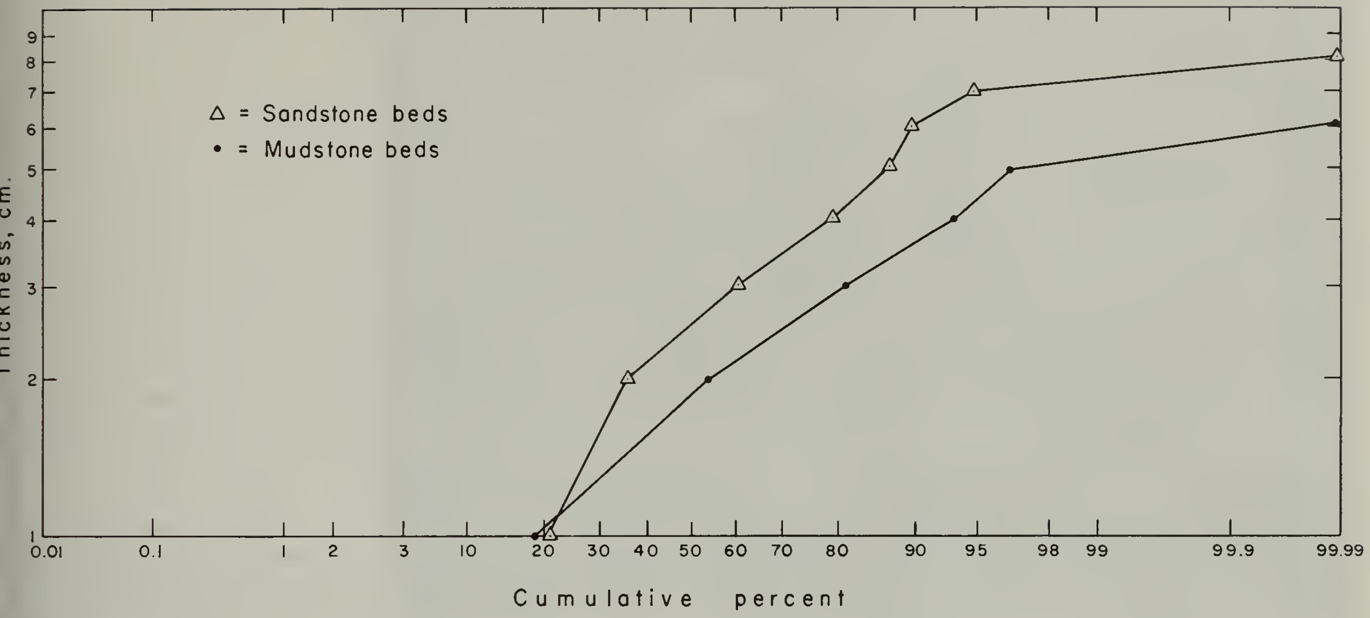


Figure 6. Log-probability plot of bedding thicknesses between 43 and 45.8 m, showing approximately a log-normal distribution.

character all beds lying above coarse conglomeratic sandstones are not thin-bedded. The thin-bedded mudstone beds are not distinguishable from other mudstones by color, sectility, or foraminiferal abundance; they locally contain scattered grains of coarse sand.

An additional feature of the mudstone sequence is an apparently rhythmic alternation of lithology. This is well displayed in beds between 137.1 and 146.6 m where dark gray mudstone and thin-bedded sandstone are interrupted at regular intervals by light grayish-brown, foraminiferal mudstone that weathers to a distinctive rusty-orange. The occurrence of the laminated rusty-weathering beds, each between 5 and 10 m thick, is rhythmic with a repetition thickness of from 7 to 12 cm. These distinctive mudstone beds are the most persistent beds in the section and can usually be traced the width of outcrop. They are slightly harder than other lithologies and usually stand in relief on weathered surfaces.

Lateral continuity of bedding. Although some beds pinch out laterally, nearly all beds studied in detail proved to be roughly constant in lithology and thickness across the 18 m of exposure. Pinch-out is inferred where sandstone beds on one bank of the creek are absent on the other, and where beds decrease in thickness away from an area of maximum development. From these features it is assumed that sandstone beds are lenticular in cross-sectional shape. Sandstone beds greater than 5 cm in thickness can nearly always be correlated across the creek but very thin beds, approximately 1 or 2 cm thick, may be present on one bank and not on the other.

Lateral correlation of beds is at places complicated by changes in lithology and structure. At 45 m, for example, a prominent (15 cm), fine-grained, light-gray sandstone is laminated throughout by charcoal-bearing silt. The laminations are gently convoluted into broad, troughlike synclines and symmetrical, rounded anticlines. On the east bank of the creek, however, the stratigraphic equivalent of this convoluted and laminated bed is three distinct beds; the lowest is charcoal laminated, the middle is silt laminated, and the upper is cross laminated. The section contains many similar examples of small-scale facies change but most are subtle and are not noticed until precise correlation is attempted.

Some beds are interrupted laterally. In figure 7 a thin claystone bed, which elsewhere separates two cross-stratified sandstone layers, is interrupted by a body of sandstone. Such structures have been termed "washouts" by Wood and Smith (1959, plate 8, figure 1). The relations (figure 7) are interpreted as follows: a current travelling from left to right has, prior to depositing the uppermost sand, eroded through or plucked out a portion of the claystone bed and removed some of the supporting sand from beneath it. A portion of the claystone layer, shown at the right, was therefore overhanging. During deposition of the upper sand the cavity was filled and inclined laminations formed. Finally, the upper sand was deposited continuously across the filled cavity.

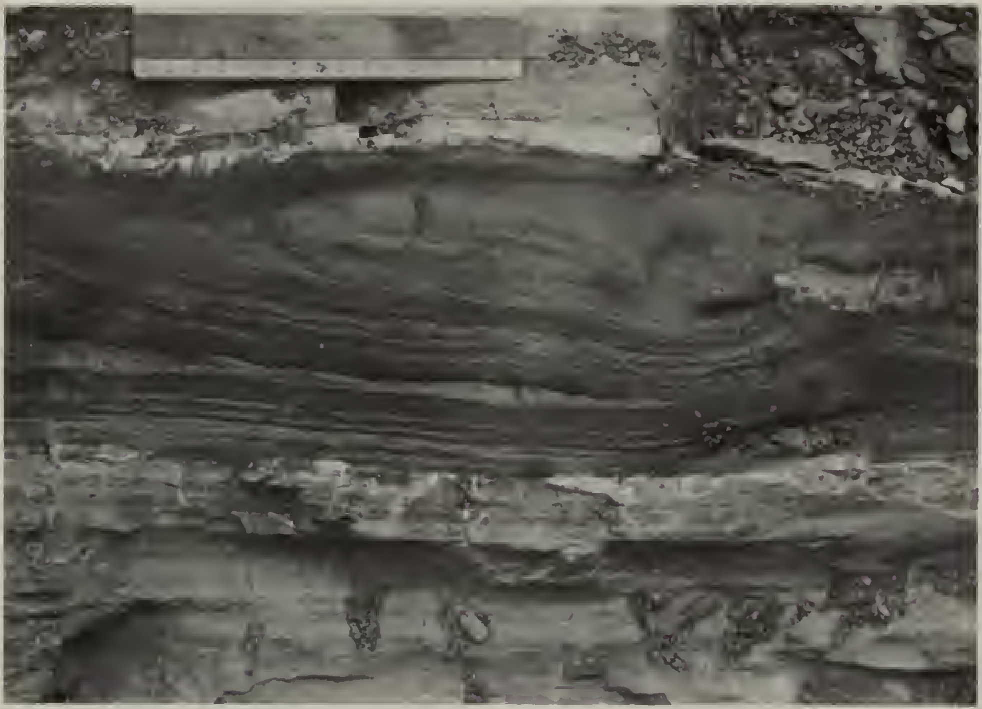


Figure 7. Ruptured mudstone layer, shown at right as an in-place remnant, and infilled sandstone near 43 m. See text. Scale is 6 inches long.

Contacts between beds. In table 2 observations on the nature of bedding contacts are summarized. Despite the unusual contacts described in later paragraphs, the typical bed-to-bed contact is a sharp and approximately planar surface and there are very few gradational contacts. Sharpness, as used in table 2, refers to the approximate thickness of the contact zone; a sharp contact is less than 1 mm thick. By planarity is meant the degree to which a 15 or 20 cm segment of the contact approaches a straight line when seen in cross section. Most contacts characterized as planar are slightly undulose, probably owing to differential compaction. Planar contacts between sandstone and mudstone are bounded on the mudstone side by a continuous lamination of darker, denser and more resistant mudstone, 0.5 to 1 mm thick. A joint parallel to bedding, usually best developed at mudstone-mudstone contacts, is either observed as a narrow crack or as a potential crack if the beds can be separated by hand. The terms "moderately well developed" and "well developed" refer to both the frequency of occurrence and the degree of perfection of bedding joints. Bedding joints, while common, are not a conspicuous feature at Santa Paula Creek probably because the rocks are poorly indurated.

Table 2. Nature of Contacts Between Beds, Pico Formation, Santa Paula Creek Measured Section.

Type of contact	Sharpness	Planarity	Bedding joint
sandstone over sandstone	rarely sharp	planarity low 1-3 cm relief	usually absent
sandstone over mudstone	sharp	approximately planar 0.5-1 cm relief	moderately well developed
mudstone over sandstone	sharp	variable	usually absent
mudstone over mudstone	exceedingly sharp	planar	well developed

Erosional contacts. Locally, the basal contacts of sandstone layers lying on mudstone reveal erosion inasmuch as laminations in the underlying mudstone are transected and the contact surface is irregular. Evidence of erosion is usually observed across the width of exposure, but in most cases, relief on the irregular surface is less than a few millimeters. Erosional contact surfaces are approximately planar for most of their extent except where several laminations or a thin bed are abruptly transected, in which case the general form may be compared to stairs with short risers and very broad treads. Where the contact surface cuts through several laminations or a thin bed, the mudstone may appear stretched, twisted, and distorted into flame-shaped tongues. In general, mudstone beneath coarse-grained sandstone is more deeply eroded than mudstone beneath fine-grained sandstone.

Deformational contacts and load structures. A contact departing markedly from a straight line in cross section is termed a deformational contact if laminations below the contact are bent but not transected by the contact surface. At Santa Paula Creek deformational contacts grade into load structures and less commonly are associated with convolute lamination and disturbed bedding. Some contacts show the effects of both erosion and deformation.

Deformational contacts are particularly common between massive sandstone beds although they are observed throughout the section. The simplest forms are slightly undulating contacts between sandstone and mudstone in which bulges of overlying sandstone (load pockets and waves) extend downward into underlying mudstone (figure 16A, right). Laminations in both sandstone and mudstone roughly parallel the irregular contact. A continuous series of forms may be observed from gently undulating contacts to bulbous load pockets (figure 16C). Extreme forms are pouches of overlying sandstone extending into underlying sandstone and attached to the overlying bed by a narrow neck. Many load structures display highly complex shapes, including several in which sandstone masses have no apparent connection with their overlying "parent" bed (figure 16B).

Only a few load structures are exposed in three dimensions. At 34.2 m small load structures, 3 to 5 cm wide and 2 to 3 cm deep, lie along the contact between graded conglomeratic sandstone and dark gray mudstone. Cross sectional shapes of the structures range from unaccentuated bulges to flattened pockets. On bottom bedding planes they appear elongated, resembling rods of conglomeratic sandstone partially imbedded in mudstone. Long axes of the structures are closely aligned with the current direction judged from nearby current bedding. These current-parallel load structures contain pebbles markedly larger than any in the overlying "parent" bed, a relationship frequently observed in load structures in the massive basal sandstones (figure 16C).

Small load pockets, with bean-shaped cross sections, are isolated within mudstone and sandstone at 50.6 and 97.2 m (figure 13). Their interiors are composed of deformed small-scale cross stratification with some minute wisps of mudstone. At 97.2 m laminations below the load pockets are broken and deformed so t seems likely that the pockets were formed by a current with sufficient strength to disrupt soft mudtone below, and, as sedimentation followed, lenses of cross-stratified fine sand sank into the unstable mud. nsufficient sand was introduced, however, to form a continuous layer, and all available was trapped and solated in the pockets.

At places, between 34 and 42 m for example, load waves between load pockets (Sullwold, 1959; 1960; Holland, 1960) are well marked and displayed an asymmetry which can be used to determine the movement sense of the current (figure 16B). Some of the load waves are marked by sharp peaks and wisps of mud pointing in a down-current direction and are termed flame structures (Walton, 1956, p. 267). Laminations in the mudstone just below the load waves are usually deformed into load folds (Sullwold, 1959) but are also disrupted. Locally, trains of mudstone chips trail downstream from disrupted flame structures and provide a clue to the mechanism responsible for adding such chips to the overlying sandstone layer.

Lamination. Most strata at Santa Paula Creek display an internal layering parallel to contacts and caused by textural or compositional changes of lesser magnitude than the major lithologic variations which form beds. This internal layering is termed lamination and is divorced from thickness connotations placed on the term by McKee and Weir (1953) and Ingram (1954).

Lamination of sandstone beds is primarily the result of abrupt changes in texture and only secondarily the result of compositional changes. The usual, although least conspicuous, textural cause of lamination is abrupt change in average grain size from fine- to very fine-grained sand or from medium- to fine-grained sand. Lamination of this type is seen on the outcrop face as trains of equal-sized grains forming lines parallel to bedding planes. These layers of approximately equal grain size are usually a few millimeters, rarely a centimeter, in thickness and are more noticeable on weathered surfaces. Wide-range internal textural changes, such as sandstone to conglomerate or sandstone to silt or clay, are also common. Discontinuous pebble layers occur in sandstone beds at 159 m for example.

Lamination as the result of clay or silt within sandstone beds is common and is distinguished chiefly by its dark color. These laminations, with a maximum thickness of 5 mm, generally show sharp boundaries and are generally restricted to fine- and very fine-grained sandstone beds. Compositional lamination, caused by variation in per cent of mineral composition of the sandstone, is rare, but lamination owing to zones rich in biotite, carbonized plant fragments, or "charcoal"-bearing silt or clay is common. These zones, which impose a marked parting to the rock, are usually from 1 to 5 mm thick, and are confined to siltstone or fine- and very fine-grained sandstone.

Lamination within dark brownish-gray mudstone beds is the result of thin intercalations of very fine-grained sand or light-colored silt. It is usually from 1 to 3 mm thick and is traceable laterally for distances of several meters. Lamination of a different type, also associated with similar mudstone, is from 2 to 5 mm thick and has a lateral extent of from 10 to 20 cm. Although this lamination also consists of layers of very fine-grained sand or coarse-grained silt, it does not parallel bedding planes perfectly, and when traced laterally terminates in very small-scale cross-stratification. The light grayish-brown, rusty weathering mudstone contains extremely minute lamination which is commonly less than 1 mm thick and so remarkably persistent that it can be traced across the width of exposure. Such lamination is defined by abrupt variations in color, by silt or charcoal percentage, or by abundance of Foraminifera.

Graded Bedding

Several types of graded bedding are present at Santa Paula Creek but the ideal type with a regular decrease in grain size from bottom to top of a bed is rare. At first glance most beds are either homogeneous and no grading is conspicuous, or else they are characterized by lamination, small-scale cross-stratification, or other structures. Sieve analysis by Natland and Kuenen (1951, p. 91), as well as careful field study with the hand lens, shows, however, that most beds are coarser at the bottom than at the top. Those with conspicuous lamination and current bedding are nevertheless commonly graded in that lower parts are coarser than upper; such beds are here defined as displaying *superposed grading*. Although graded bedding occurs predominantly in sandstones at Santa Paula Creek, many thin beds of mudstone are also graded. These show a regular transition from coarse silt at the base to clay at the top.

Most of the types of graded beds recognized by previous workers (Kuenen, 1952, 1953a, 1953b; Ksiazkiewicz, 1952, Radomski, 1958) occur in the Santa Paula Creek exposures, as well as some new ones. The types occurring are: (1) Ideal or continuous graded bedding (Kuenen, 1953b, figure 1A; Ksiazkiewicz, 1952, figure 1A) with both good and poor separation (Ksiazkiewicz, 1952, figure 1A and 1B). (2) Discontinuous graded bedding in which the fine-grained upper portion or a medium-grained central portion is missing (Kuenen, 1952, 1953b, figure 1B; Ksiazkiewicz, 1952, figures 1C, 1D). In this type there are one or more surfaces within the graded bed across which a sudden decrease in grain size takes place. (3) Symmetrical graded bedding (Ksiazkiewicz, 1952, figure 2C) in which the grain size decreases both upwards and downwards from a zone of maximum coarseness near the middle of the bed. The vertical position of this zone within the layer may be quite variable. (4) Pen-symmetrical graded bedding (Ksiazkiewicz, 1952, figure 2D, 2E) in which the lower part of the bed consists of fine-grained sandstone, apparently ungraded, topped by a graded unit. (5) Multiple or recurrent graded bedding (Ksiazkiewicz, 1952, figure 2A; Kuenen, 1952, 1953b, figure 1D) in which the bed consists of several graded units with the maximum grain size in each succeeding unit slightly less than in the underlying ones. (6) Graded bedding with lenses, in which a graded bed contains thin isolated lenses of coarser material at any height, is fairly common. This type has not been reported by Kuenen (1952, 1953b), Ksiazkiewicz (1952), or Radomski (1958). (7) Graded bedding with silt intercalations is an additional type in which the graded bed is interrupted at one or more levels by thin intercalations of charcoal-bearing silt and fine sand.

These descriptive types of grading are in some cases gradational one into the other, and some exposures exhibit elements of several. Some types do not strictly refer to single beds but to sets of beds between mudstone layers. The pen-symmetrical type, which Ksiazkiewicz (1952) and Radomski (1958) apply to a single bed, might by some observers be recorded as two sandstone beds: a fine-grained sandstone succeeded by a graded sandstone. Further difficulties arise in recognizing marginal cases of superposed grading in which, for example, a single bed of nearly uniform lithology but a few centimeters thick displays lamination at the base and small-scale cross-stratification at the top. In clear-cut cases of superposed grading the diminution of grain size upwards is gradational through the various other structures, but in marginal cases the transition from one predominating structure (such as lamination) to another (such as small-scale cross-stratification) is so sharp that some observers would record two distinctly different layers.

Small-Scale Cross-Stratification

Throughout the Santa Paula Creek section small-scale cross-stratification (McKee and Weir, 1953), commonly called current bedding,* is conspicuous and measurement of its orientation has been the chief source of paleocurrent information. It is especially well developed between 43 and 45.8 m. The cross-

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* Many terms have been used for this structure and its varieties, but frequently without distinction between external form and internal structure, or between description and inferred origin. Some of these usages are: *ripple-drift bedding* (Sorby, 1908), *ripple* cross *lamination* (McKee, 1939), *current bedding* (Kuenen, 1953b; Wood and Smith, 1959, p. 170), *ripple bedding* (Dott, 1963, figure 13), *current ripple bedding* (Kuenen, 1953b), *current ripples* (ten Haaf, 1956, p. 193; Dott and Howard, 1962, p. 119), *current ripple marks* (Sanders, 1960, p. 419), *current stratification* as a genetic type of cross-stratification (Crowell, 1955, p. 1361; Hsu, 1960, p. 581; Dott, 1963, p. 118), *climbing ripple* and *current-ripple cross-lamination*, as varieties of cross-stratification (McBride, 1962, p. 51). Although many of these terms are synonymous, some are varieties or species of the generic and descriptive term *small-scale cross-stratification*. A study and classification of these structures is long overdue.

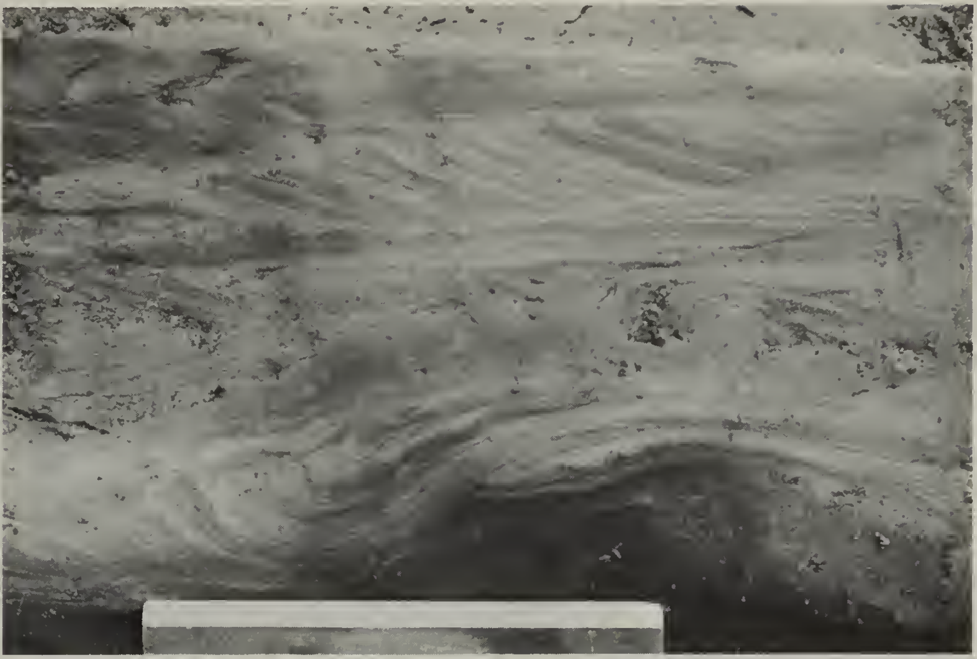

Figure 8. Small-scale cross-stratiication and contorted stratification ear 43 m. The upper tier of cross-trata indicate a current component rom left to right. The oversteepened nd deformed cross-strata at the ase suggest drag from left to right. cale is 6 inches long.

tratification is generally confined to fine- and very ine-grained standstone beds with a relatively high lay and silt content. Some of the cross-stratified beds re subtly graded and show a transition from fine and at the base to very fine sand and silt at the top. The cross-stratification is delineated by dark zones hat are rich in biotite, clay, or carbonized plant fragments. In fact, there appears to be little basis for the ft-repeated statement (Bailey, 1930, p. 85; Pettijohn, 957, p. 176; see also discussion in Dott, 1963, p. 118; Packham, 1954, p. 466) that graded bedding and current bedding are uncommon associates.

Both upper and lower contacts of cross-stratified eds may be irregular. The lower contact is commonly an erosional disconformity with slight relief n the surface, and the upper contact irregular because f preserved ripple marks.† Whereas thicknesses of ross-stratified sandstone layers vary greatly, the combined thickness of a couplet consisting of a cross-tratified sandstone at the base and an overlying claytone is nearly constant across an exposure. Because he upper contact of this couplet is approximately a lane surface, a complementary thickness relationship xists—where sandstone is thick the overlying claytone is thin and where sandstone is thin the claystone s thick.

A common form of cross-stratification begins above n erosional lower contact with subparallel laminated andstone succeeded by well-developed sets of cross-strata with ripple marks. The nature of the transition from laminated sandstone to cross-stratified sandstone is usually obscure but in a few examples the cross-strata under the gently dipping surface of the ripple lie approximately parallel to the underlying lamination. Beneath the steep foreslope of the ripple the "foreset" cross-strata rest with angular discordance on underlying laminations and in some instances the foreset laminations lie on a scoured surface. The spacing and height of ripples are generally not regular but in several examples crest-to-crest spacing is from 5 to 15 cm. In some beds a long-spaced earlier set of crests has been succeeded by a second short-spaced set.

In many beds the ripplemarked surfaces, which form the upper boundary of the sets of cross-strata, are not entirely preserved although portions may be detected within the bed. Whole beds, or the upper parts of graded beds, may consist entirely of small-scale cross-strata in an arrangement complicated by scour of pre-existing ripples and deposition of younger sets of cross-strata on the scoured surfaces. Another type of cross-stratification, illustrated in the lower part of figure 13, occurs in beds of irregularly laminated very fine-grained gray sandstone and dark brownish-gray mudstone. These forms are termed "climbing ripples" because the local surface sloped upwards gently in the down-current direction during growth stages and there is no indication of scour between sets. The usual crest height is from 0.5 to 1 cm and the width is 1 to 2 cm. Sets of cross-strata are visible under the rippled top surface and are delineated by laminations

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The term *ripple mark* is used here for the external ripple form, whether observed in cross-section or in plan or relief on a bedding surface. Although the term *ripple form* is preferable in some ways, *ripple mark* is too well established to be abandoned.

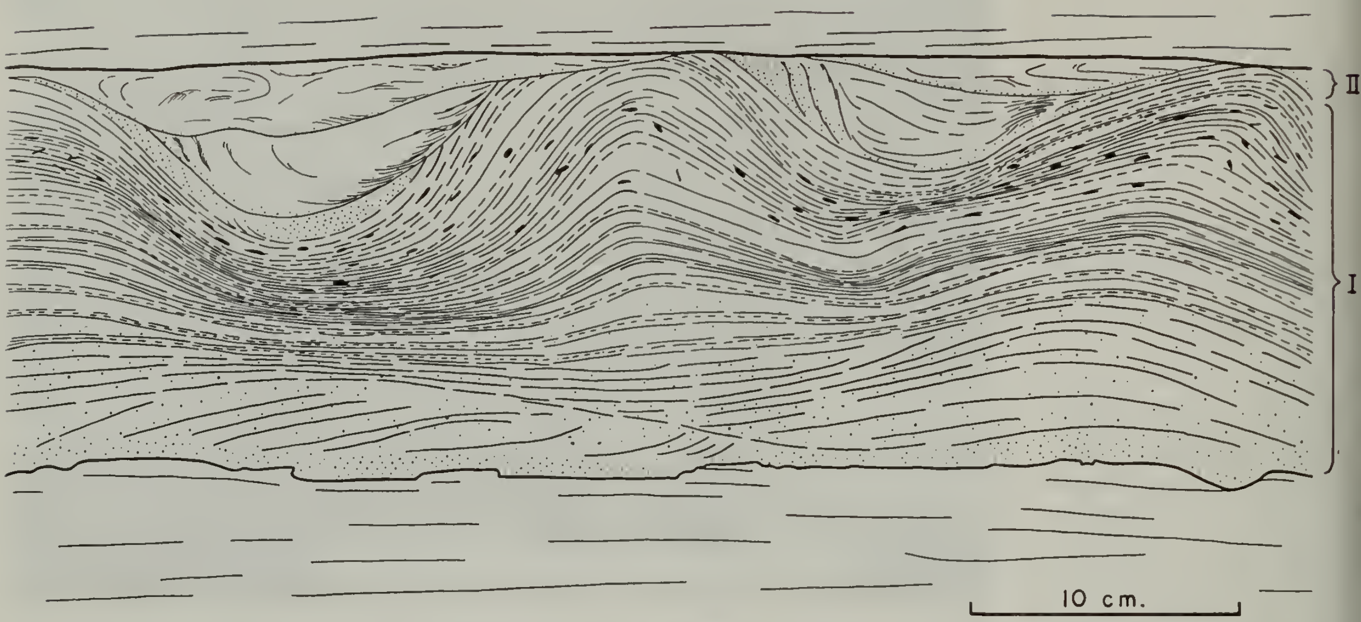


Figure 9. Sketch of bed with convolute lamination at 45.5 m. The depositional unit (I and II) is separated by heavy lines from laminated claystone and siltstone above and below. In the thicker and lower sub-unit I, small-scale cross-stratification grades upwards into undulose parallel laminations which are convoluted at the top. Flecks of carbonized plant material, shown as black spots, are less well aligned along the traces of the axial surfaces of the anticlines. The current sense at the base is obliquely out from the plane of the sketch at an angle of 60° to the left or west. In the sets of cross-strata above the convolutions (II) the current sense is variable but generally to right or east.

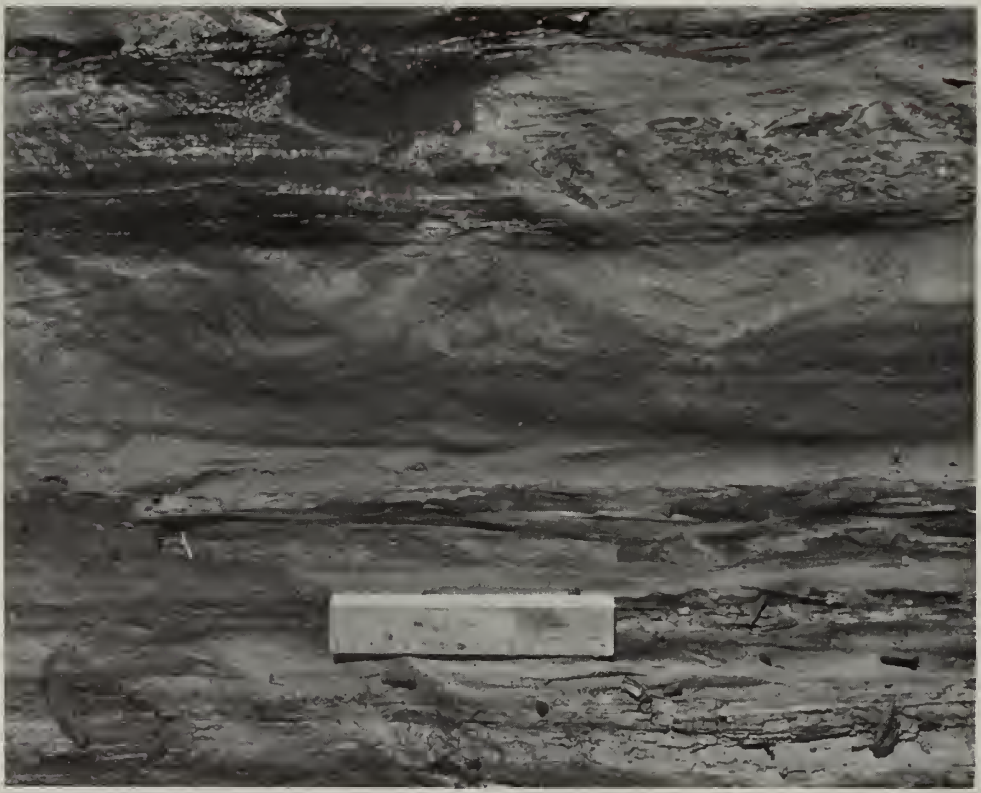


Figure 10. Convolute lamination and cross stratification at 45.5 m.

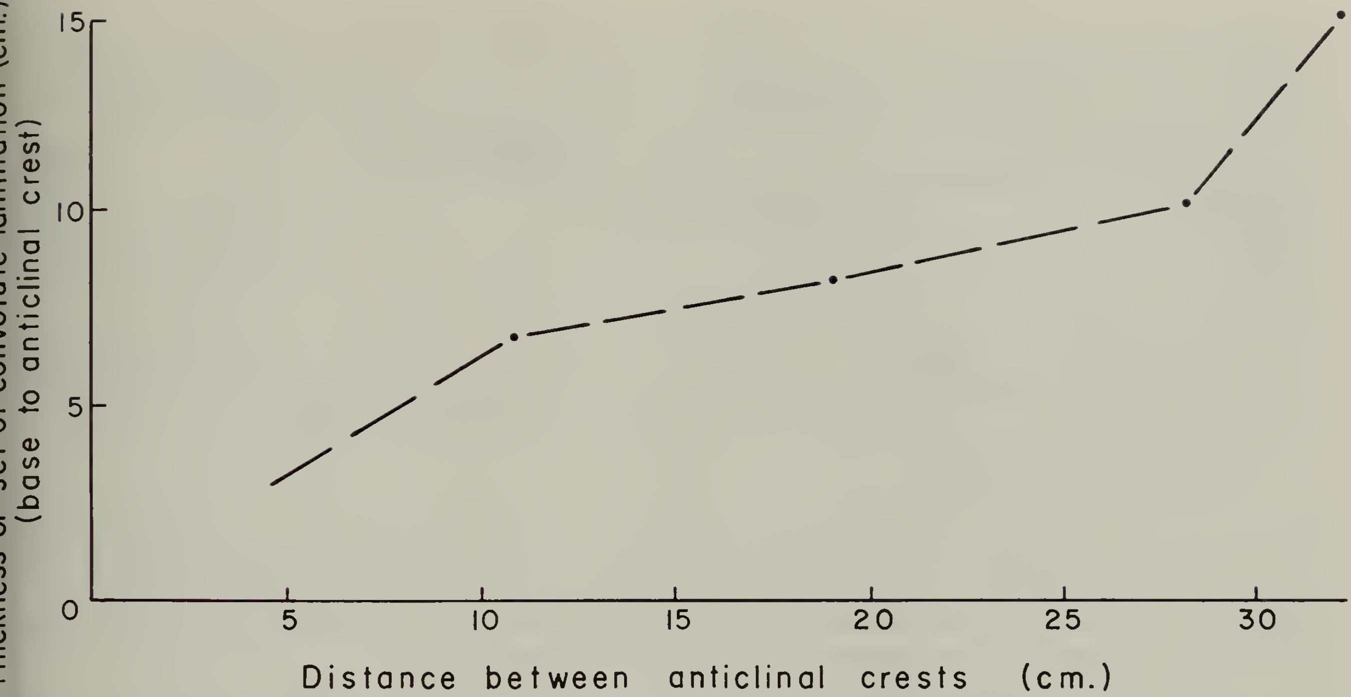


Figure 11. Relation between thickness and wave length of convolute lamination. Four sets, found in separate layers between 48 and 85 m, are cluded.

f silty clay which extend upward from underlying udstone. In many examples the ripple marks grade the up-current direction into laminated sandstone aving a lateral extent of 10 to 20 cm.

Ripple marks are poorly exposed on bedding surices at Santa Paula Creek so that the plan arrangeent is not well known. Observations made by cutting rough ripple marks parallel to the bedding, however, ggest that each ripple is more or less isolated from s neighbors and has the shape of an oval mound of diment, slightly elongate at right angles to the curent and with a steeper dipping surface on the downrrent side.

Deformed and oversteepened rippled surfaces and ts of cross-strata are fairly common in the exposures udied. Figures 8, 9, and 10 show cross-strata overeepened and wrinkled within the synclines of a conlute bed. Deformed cross-strata occur as well near e tops of cross-stratified beds.

Convolute Lamination

Many beds in the Santa Paula Creek section display ernal lamination that is intricately curled, crinkled, d convoluted, but which is limited to the interior a bed only and does not affect the upper and lower ntacts (figures 9 and 10). The term *convolute lamition* is applied to this structure, as a variety of *conrted stratification* (Dott and Howard, 1962, p. 120). e convolutions range from slight undulations to high waves with detached crests and are locally associated with sets of cross-strata which may be overturned and deformed within the folds. Most beds with convolute lamination show minor breaks in deposition (micro-unconformities) and some displacements (microfaults). Convolute lamination at Santa Paula Creek was apparently formed during current deposition of the bed containing them and before the next bed was laid down. In practice these limits on time of formation are critical in terminology for if several beds of sandstone with intervening mudstone layers are included in the deformation, the structure is referred to as disturbed bedding, inasmuch as it has developed on the sea-floor after deposition. A few layers with convolutions grade laterally into disturbed beds. Convolute lamination has been described primarily by Kuenen (1953b, p. 1056), ten Haaf (1956), Wood and Smith (1959, p. 170), Sanders (1960), Dott and Howard (1962), and McBride (1962, p. 52).

Beds with convolute lamination are best developed at Santa Paula Creek from 42 to 56 m, 90 to 107 m, and 164 to 177 m, parts of the section characterized by rhythmically interbedded sandstone and mudstone. Convolutions usually occur in beds somewhat thicker than those in the immediate vicinity, and are remarkably persistent in character and thickness across the width of exposure. In fact, this persistence is one of the features precluding post-depositional folding and shortening, for in cross section the length of individual laminations is very much greater than the length of

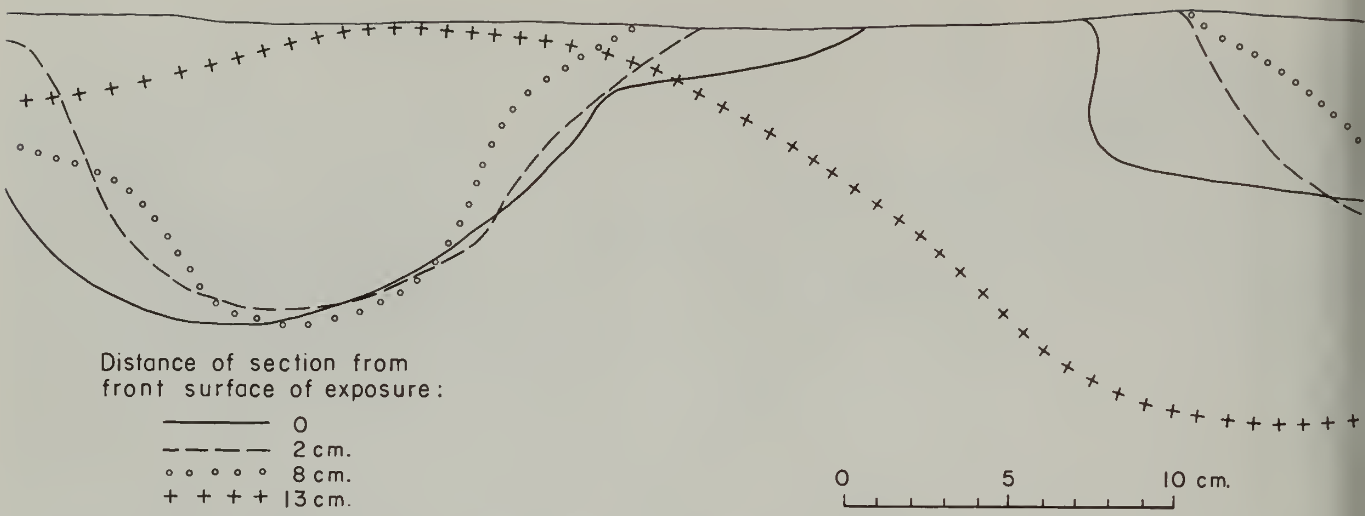


Figure 12. Sections of bed with convolute lamination at 45.5 m. The sections are drawn on the upper contact of the convoluted sub-unit. Successive positions are depicted on the outcrop surface and at 2, 8, and 13 cm back from the surface.

the containing bed. Although in most examples studied there is no evidence of dying-out laterally, at 54.9 m the convolutions disappear into a laminated layer to the west, and into disturbed bedding on the east. In four layers a correlation was found between bed thickness and wave length of convolute folds (figure 11).

Convoluted zones within beds consist of subparallel laminations which pinch and swell in thickness as they outline the folds and other structures but do not include cross-stratified portions. Cross-strata are commonly associated, however, and are found principally within synclines where deposition has prevailed after the formation of the folds. A common sequence consists of a basal subunit of cross-strata which die out upward into undulose laminations that define the principal zone of convolutions. Cross-strata, commonly deformed within synclines, succeed the convoluted zone with a micro-unconformity; locally there is a discrete erosion surface on the top or flank of a convolute fold which was formed before deposition of the overlying cross-stratified unit. In some beds the upper cross-stratified layer is continuous and truncates the tops of anticlines. The sets of cross-strata are therefore thickest over synclines and in proceeding upward are less and less influenced by the irregular convoluted surface. In short, the couplet formed between a convoluted subunit below and a cross-stratified subunit above is of approximately constant thickness along a bed.

Layers with convolutions display asymmetric anticlines and synclines. Anticlines are usually narrower than synclines and range from barely perceptible arches to high steep-sided folds. A few anticlinal crests are pinched off from their bases and form isolated bodies. In most beds the laminations are thinnest in synclinal troughs and thickest in anticlinal crests. The intensity of apparent folding increases upwards from the base so that convolute anticlines die out downwards. Most anticlinal crests have been planed off by erosion and micro-unconformities and micro-scours are formed on their upcurrent limbs.

The degree of asymmetry and direction of tilting of successive folds varies laterally within the same bed at Santa Paula Creek. As a rule, axial surfaces lean in a down-current direction, as determined from small-scale cross-stratification in associated layers. There are, however, a few puzzling sets of folds which lean in an up-current direction. In high, steep anticlines there is usually a much greater uniformity in the direction of axial-surface tilting than in shallow anticlines. Most axial surfaces are curved with the concave side on the down-current side; the radius of curvature of the line of intersection of the axial surface and the outcrop surface usually decreases upwards as well. In three dimensions the convolutions appear to be irregularly shaped domes and depressions (figure 12).

Convoluted units usually are composed of medium-grained sand and finer, although fine-grained sand may be the coarsest fraction present. Although silt and clay are invariably present within interstices, convoluted zones in layers predominating in silt have not been recognized. The interior of isolated small pod of fine-grained sandstone in thinly interlaminated sil and clay is also convoluted (figure 13).

Kuenen (1953b, p. 1056) first described convolut lamination and attributed the formation of the struc

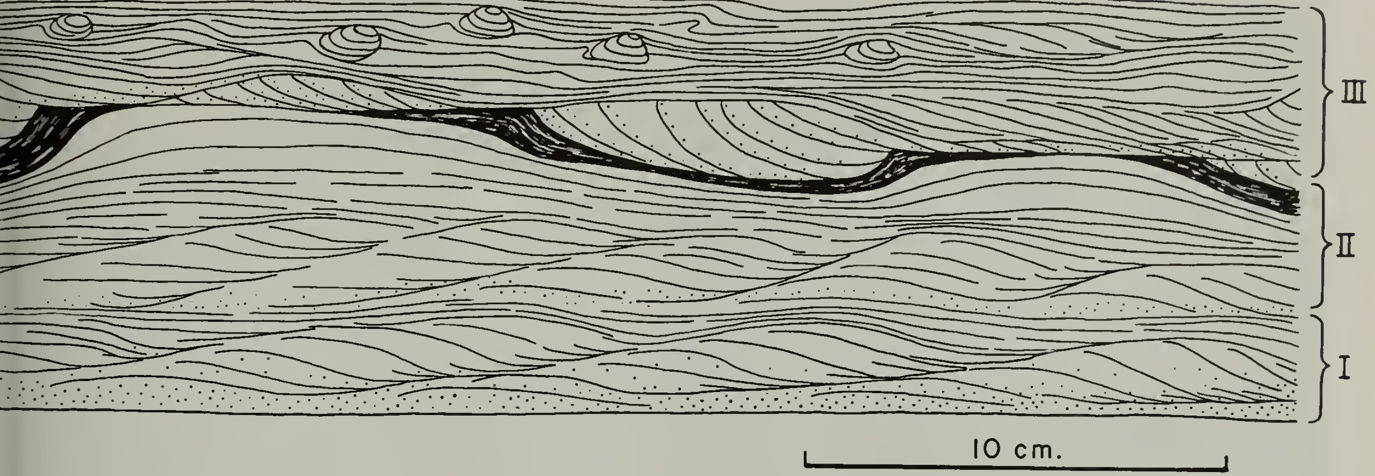


Figure 13. Sketch of bed at 50.6 m. The two lowest sub-units (I and II) display small-scale cross-stratification (variety: climbing ripples) which · out upward into undulose lamination. Sub-unit II is topped by two broad anticlines, in turn capped by a dark silt and clay layer. Sub-unit with cross-stratification at the base, grades upward into a portion with undulose laminations and isolated load packets with somewhat convoluted eriors.

re to intensification of ripple marks by a current hich exerted a vertical suction on the crests and pres- re in the troughs. Depression of the troughs was rther effected by load deformation. The convolute minations in the Aberystwyth Grits of Wales were nsidered to be independent of cross-stratification Vood and Smith, 1959, p. 170). Sanders (1960) und that convolutions had formed in predominantly ry fine sand to coarse silt layers. These grain sizes in the critical range above which grain-mass over- dows intergranular cohesion and below which the verse is true. Layers of very fine sand and coarse are highly metastable immediately after deposition. nders hypothesized that convolutions were formed currents which exerted frictional drag on the sedi- ntation surface. The crests of the convolutions reby received the full force of the current and were oded while concomitantly the troughs were filled h current-laminations. Hence, the sedimentation face, in response to friction, tended to develop re- f, while erosion and deposition tended to diminish ef. The forming of convolute laminations therefore parently depends on fluctuating currents. Dott and ward (1962, p. 120) distinguished more clearly be- een gravity-induced and current-induced effects l attributed the formation of convolute lamination a combination of the two processes. Convolute lam- tion grades into mass flow as current deformation omes subordinant to gravity-induced deformation ott, 1963, p. 110).

The conditions implied for the origin of convolute ination at Santa Paula Creek suggest that very fine fine sand was deposited by a fluctuating but wan- current. At first the sand was deposited as individual grains with either subparallel lamination or cross-stratification. As more material was deposited, the laminated sediment acquired some cohesion as the particles settled together. Continued movement of the current across the newly deposited sediment deformed the laminations to form convolutions. Individual grains were locally eroded from growing anticlines and, along with grains falling out of the current, were deposited within synclines as cross-strata. Last of all, as the current waned, the depositional surface became smoother and sets of very fine sand and silt cross-strata were deposited. These uppermost cross-strata were highly deformed but did not lose cohesion. Since no further sediment was deposited during this sedimentation episode, cohesive forces due to compaction were probably of small magnitude so that weak currents were able to deform them.

The presence of sets of overturned cross-strata within the convolute troughs indicates that the convolute laminations at Santa Paula Creek formed during current deposition. Disturbed bedding caused either by current impact or drag or by mass movement may have formed during or shortly after the convolutions, and may be superimposed on convolute lamination.

Sole Marks

Grooves and flutes are rarely observed in the Santa Paula Creek section because bedding surfaces are seldom exposed. The few grooves noted (figure 14) are cut into the tops of mudstone layers and are revealed when the soft covering sand is eroded away. They are therefore grooves and not groove casts or molds. If the sandstone layers were to become cemented, as

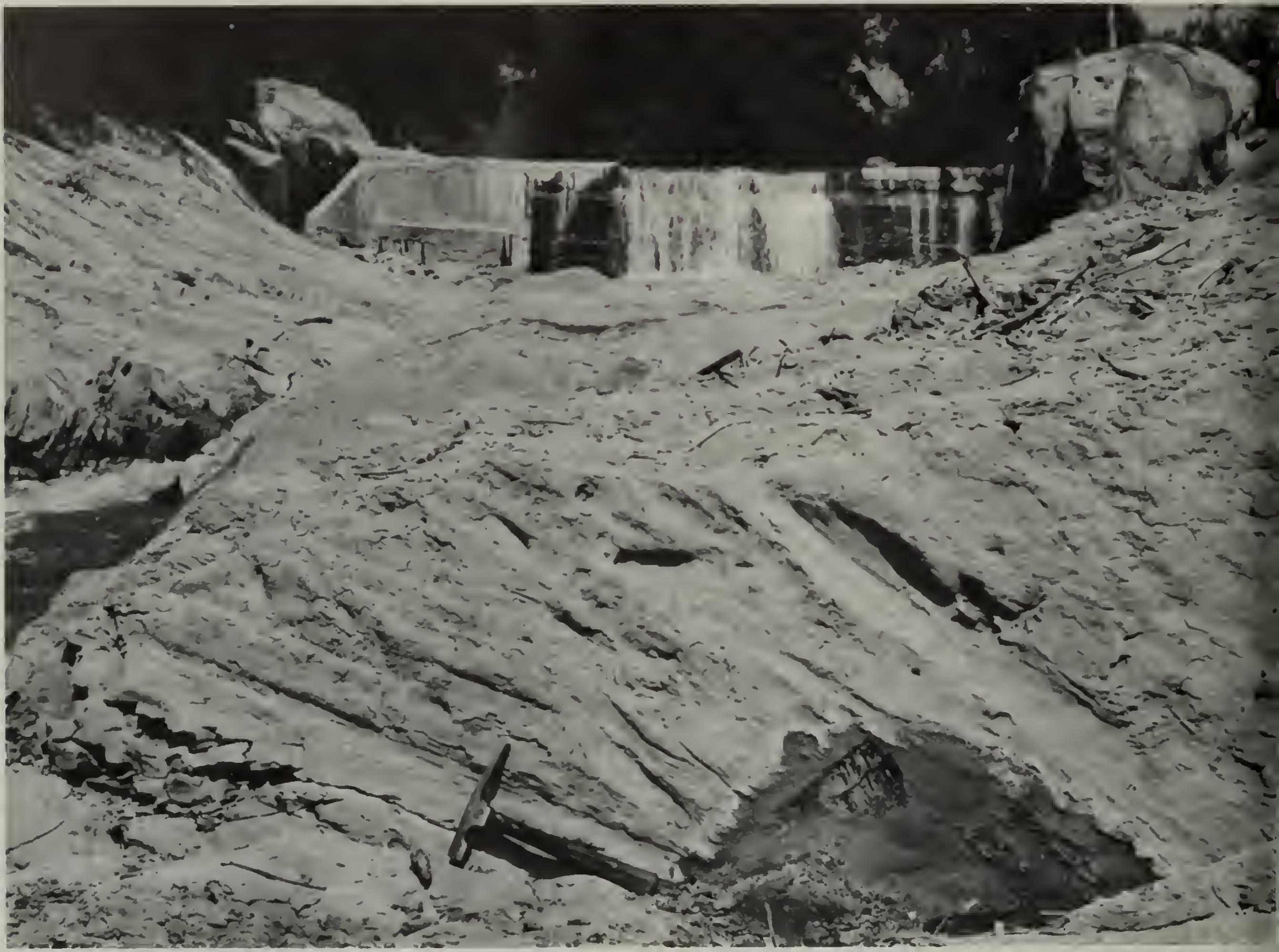


Figure 14. Grooves on upper surface of mudstone layer near 50 m. Photograph taken in 1957. Note the slight variation in direction of the sets of grooves, and the remnant of covering sand to the right of the hammer.

in most Flysch-type sequences, the soles of the layers would perhaps reveal abundant marks when softer shale had weathered away. It is quite certain that grooves were formed when clasts (coarse sand grains, granules, and larger) moved across mudstone, for some grooves end at such clasts and display a cross-sectional shape compatible with the shape of the tool.

Disturbed Bedding

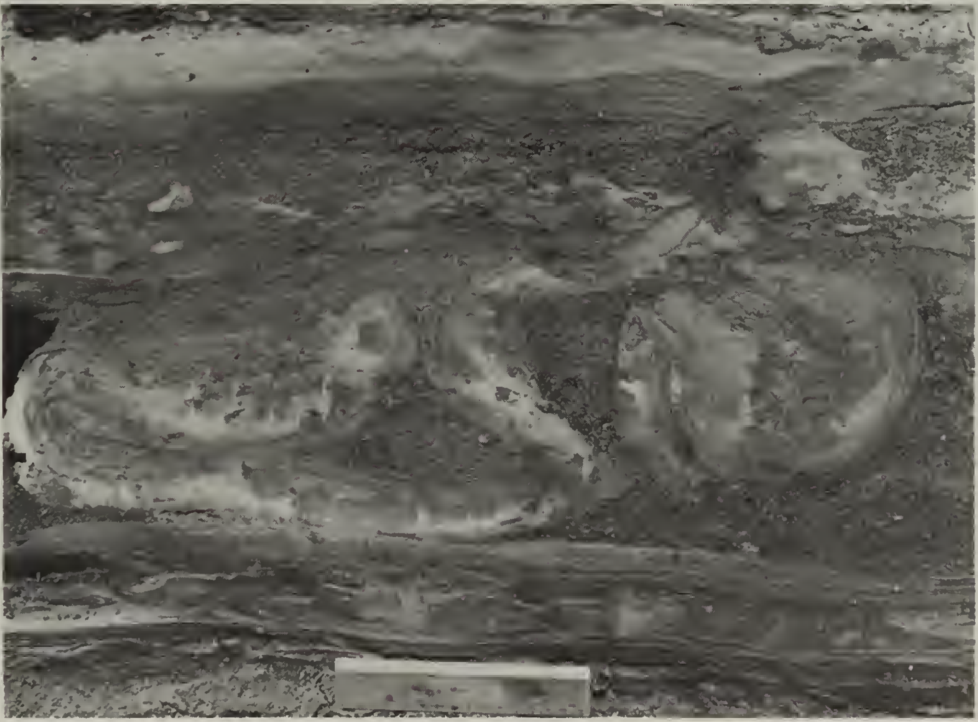
Many beds or series of beds at Santa Paula Creek include parts that have been disturbed after they were deposited but before they were wholly consolidated, and before tectonic deformation. The term *disturbed bedding* is used here with a descriptive meaning exclusively to apply to post-depositional soft-sediment deformation (McBride, 1962, p. 53), preconsolidation structures (Kuenen, 1953a, p. 21) or slump structures (Kuenen, 1953b, p. 1054). It is a major subheading under *contorted stratification* as defined by Dott and Howard (1962, p. 120; see also, McKee and other 1962, p. D151). It is applied to deformation whic took place after a bed was deposited and includ folding, faulting, and fragmentation before successi layers were laid down across the disturbed zone a though in some examples the disturbed parts are e veloped in an undisturbed matrix. This contrasts wit *convolute lamination* where the deformation affecte laminations within a single bed and occurred befo final deposition of the bed was complete. Where be with convolute lamination pass laterally into disturb bedding, however, this distinction may be difficu and impractical. It has not appeared useful here discriminate specific types such as prolapsed beddi (Wood and Smith, 1959, p. 172), sealing-wax or flo structure (Fairbridge, 1946, figure 1), because of gr dation and overlap between types, although the varieties of disturbed bedding occur at Santa Pau Creek.

Disturbed bedding is found in all parts of the sec- n at Santa Paula Creek in zones that range from m to 60 cm in thickness and usually include several uplets of sandstone and mudstone. The deformation iges from minor folds through tight folds and faults nearly complete fragmentation of beds. The lithol- y of the beds within as well as immediately over- ng and underlying disturbed layers is not signifi- ntly different from that elsewhere in the section cept that sandstone is more abundant and commonly arser.

The top of a disturbed zone is usually marked by ayer of cross-stratified fine-grained sandstone from o 3 cm thick, and small irregularities in the surface the disturbed zone are filled and smoothed by this erally continuous layer. At one place (48.6 m), wever, the end of a large mudstone slab protrudes ward into overlying strata for 2 cm; sand and mud ve filled in around it but there is no indication of cible intrusion of the clast after the overlying sedi- nts were deposited. In all examples the paracon- rmable nature (Dunbar and Rodgers, 1957, p. 119) the upper contact shows that the deformation took ice on the sea floor before succeeding layers were posited. In several examples, however, disturbed ers are contained in an undeformed matrix of sandstone; these beds, including both disturbed layers and sandstone, are here referred to as disturbed bedding.

An intestiniform example of disturbed bedding at 48.6 m, which ranges in thickness from 25 to 45 cm, has been studied along the 20 m of its extent (figure 15), and is similar to five others elsewhere in the section. In it two separately contorted layers and a lens of mudstone clasts lie within a sandstone matrix and are truncated by a layer of sandstone on top. The matrix sandstone is graded in places and ranges in grain size from granules to medium sand, although on the whole it is poorly sorted and contains discernible mud, biotite, and organic fragments. This sandstone extends laterally beyond the disturbed zone where it becomes somewhat more reddish in color and both laminated and graded. The grains of the sandstone, where in contact with the underlying persistent mudstone, are pressed into it but no grooves or slide marks were noted. The contorted layer (figure 15) consists of laminated siltstone and claystone. It correlates with a layer (3 cm thick) to the east that underlies the matrix sandstone beyond the extent of the disturbed area. In fact, the crumpled part appears to have been detached from the breached crest of a gentle anticline in this layer which was breached during the vigorous process of sand emplacement. Large

Figure 15. Intestiniform layer at 48.6 m. Note that the deformed layer of mudstone lies in a normal depositional relationship with the underlying layers to the left of center. It is entombed within graded sandstone and then is overlain by a layer of mudstone-chip breccia, also contained within a matrix of sandstone. The sandstone in turn is capped by layers of mudstone and sandstone with small-scale cross-stratification, indicating a current sense from left to right.



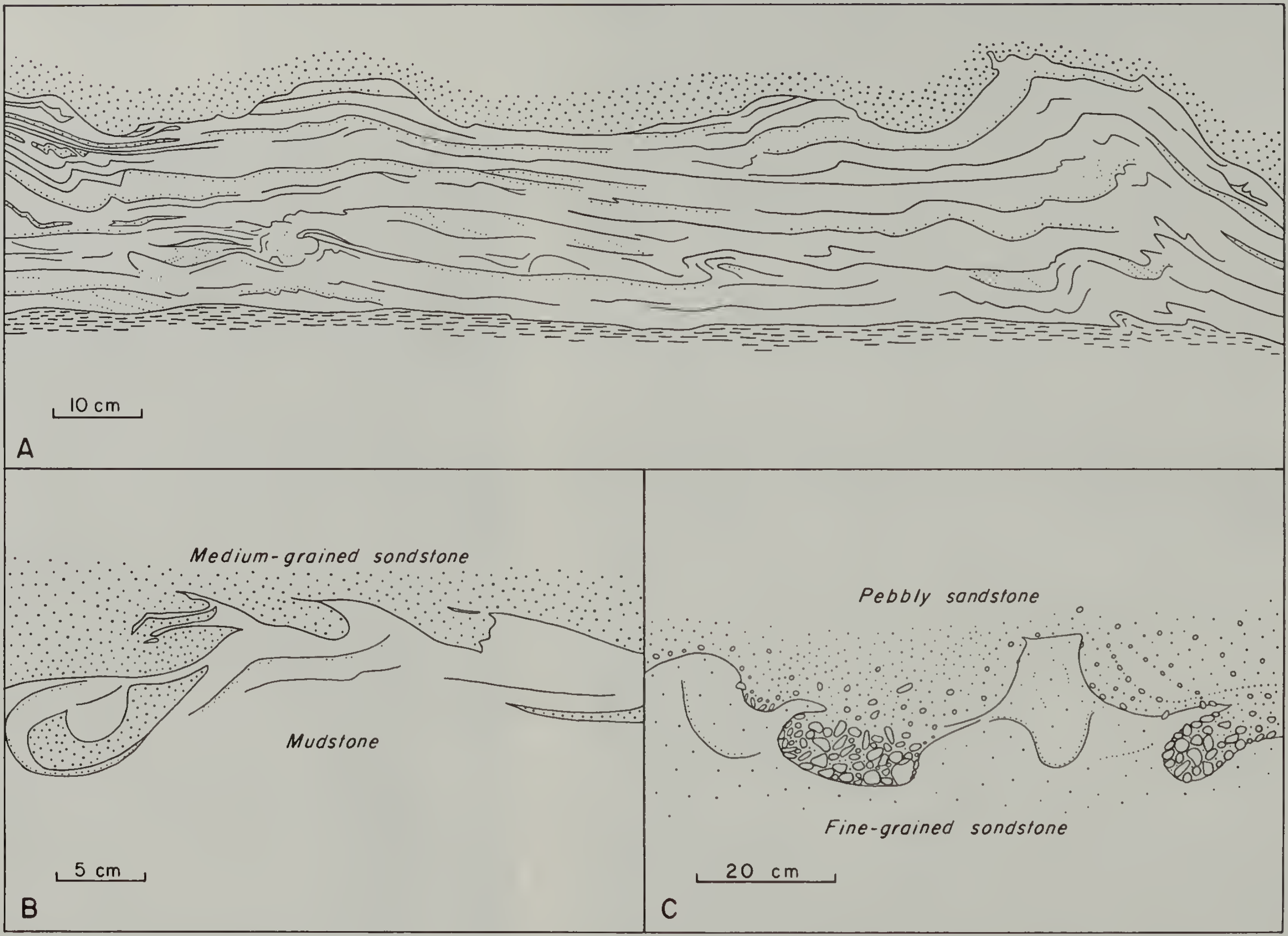


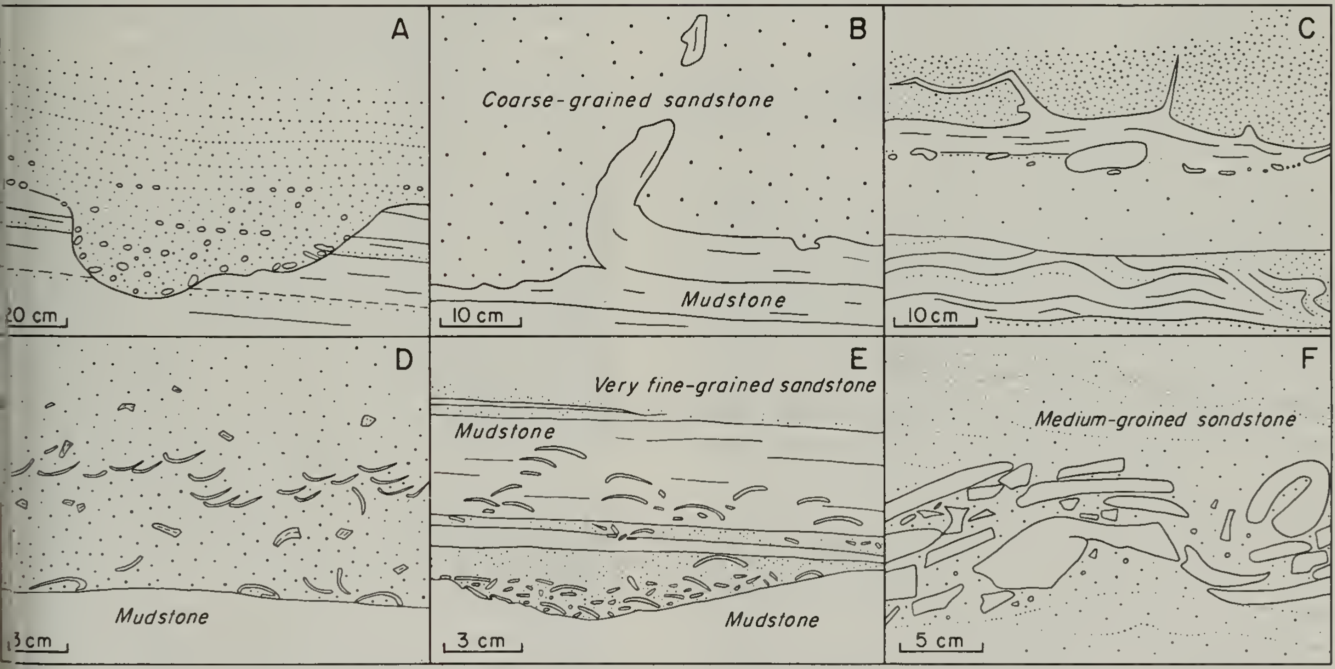
Figure 16. Sketches of sedimentary structures, I. A: Deformation of interbedded sandstone and mudstone near 48 m beneath a sandstone layer with wavelike load forms at its base. See text. These structures are interpreted as the result of erosion impact, and drag when the overtopping sandstone was emplaced by a current moving from right to left. B: Flame structures at base of massive sandstone at 31 m suggesting drag from right to left. The upper part of the underlying mudstone contains diffuse deformed layers and masses of very fine-grained sandstone and siltstone. C: Load pockets near 16 m.

udstone clasts in the lens which overlies the intes-
iiform layer match lithologically and were probably
so torn from these breaches. At places in this dis-
rbed zone, but outside of figure 15, a contorted
yer (1 cm thick) consists of a reddish-brown foram-
iferal mudstone and is the lithologic counterpart of
layer beneath the 3 cm stratum. Disrupted pieces
it are scattered throughout the matrix.

Two broad lenses and several smaller bodies of mud-
one-clast conglomerate lie in the upper part of this
sturbed zone. The angular mudstone fragments, some
which are interlaminated claystone and siltstone,
nge up to more than 10 cm in length and are em-
dded in a matrix of very coarse sandstone. These
nses flank the center of the disturbed layer where
e contortion is greatest and some small bodies are
ught within overfolds. The upper contact of the
nses, as well as that along the top of the central
ntorted zone, is scoured and covered by a graded
edium-grained sandstone layer. Although similar
hologically, it forms a distinctly later layer than the
atrix sandstone and is in turn overlain by a cross-
ratified sandstone layer between 2 and 3 cm thick.
Most of the folds in this intestiniform bed, which at
aces are very complicated, have axial surfaces which
p to the east although some dip to the west. In
neral, therefore, the inferred sense of movement is
om east to west and if the folds are "unraveled" the amount of shortening normal to the fold axes is 41 percent. A plot of the orientation of 15 fold axes shows a scatter of only 20 degrees to either side of a marked cluster, striking N 35 W when rotated back to horizontal around the present strike of the beds. The position of the cluster, as well as the orientation of individual axes, indicates a plunge of a few degrees toward the southeast into the bedding plane; in short, the axial lines do not everywhere lie parallel to the bedding below.

Other zones of disturbed beds at Santa Paula Creek show deformation both less extreme and more intense. At places a layer has slipped from its substratum and skidded to form folds, locally gentle and elsewhere compressed and thrusted. These displaced beds may be completely fragmented and in turn slurried (Wood and Smith, 1959, p. 172–173). Curled sharp and jagged ends of mudstone layers, peeled up from the bed below, extend into a matrix of sandstone (figure 17B); these relations suggest that when the sand was emplaced, fragments of mudstone were carried bodily away.

Several observations bear on the origin of these disturbed beds. Sandstone, including coarse sandstone with granules, is more abundant at the zones of disturbance than elsewhere in the section. The folded layers of mudstone are engulfed in graded sandstone and near at hand are lenses of mudstone fragments,



gure 17. Sketches of sedimentary structures, II. A: Scour channel at base of laminated pebbly sandstone near 20 m. B: Overfold of mudstone at base of massive coarse-grained sandstone near 18 m. C: Layer of pebbles along bedding plane near 151 m. See text. D: Imbricated shells, cave up within bed, at 43 m. Many disarticulate valves are oriented with hinge up-current. Current moved from left to right. See text. E: Shells, cave down, at 198 m. See text. F: Imbricated mudstone slabs near 14 m, current from left to right.

also in a sandstone matrix. These associations strongly suggest that the disturbance is the result of the arrival of a vigorous current laden with relatively coarse material upon a partly consolidated floor of interlayered mudstone and sandstone. Perhaps strips of mudstone were peeled up and lifted bodily by the current, complexly folded and fragmented, and then supported in a layer of settling sand, which is preserved as the graded matrix. The sudden arrival and tractive force of the invading current appears to have been as much responsible for the disturbed zone as the existence of an initial slope.

Some of the Santa Paula Creek exposures can be interpreted as stilled views of this process. Several features, for example, suggest that currents moved along the basin floor in tongues or filaments with higher velocities. Figure 14 shows large grooves oriented parallel to currents which not only gouged and scraped into the substrate, but also sank slightly into the material where soft. Scour channels (figure 17A) formed beneath current threads more vigorous than parts to either side, and where the substrate was relatively firm. These bottom-hugging filaments carried and sorted the largest clasts which then accumulated within the scours. Where the substrate was hydroplastic and soft, the filaments sank into the bottom, forming load pockets (figure 16C). Several of these upon dissection display a rough orientation parallel to the current, although most are too irregular to show much linearity. At one place (65.4 m) a fold has clearly originated with an orientation parallel to the current, for downfolding has followed a linear load cast. It seems quite likely that these processes may account for fold axes lining up approximately parallel to the bottom currents (figures 18 and 19). In short, the folds in disturbed layers may have been born with their axes parallel to high-velocity threads within the currents.

It is possible, however, that the disturbance had actually started before the arrival of the sand-laden current. A triggering event, such as a sharp earthquake, may have set off both the current and the deformation simultaneously. When the current arrived at the site of the disturbed beds, the sand worked its way within the folds, perhaps modifying them. Despite these possibilities, an origin due largely to the force of impact and traction of the current is preferred. For this reason the term *slump structure* is avoided and the nongenetic and purely descriptive term *disturbed bedding* is adopted. It is doubtful that the relative role of incisive current impact and downslope mass movement under gravity alone can be evaluated. All gradations can be expected between examples where downslope movement was merely triggered by a current to examples where the current, moving along a flat basin floor, was vigorous enough to cause deformation where there was no slope at all. Moreover, it has not everywhere been possible to determine the orientation of load forms, flame structures, and other linear features in order to relate them to current or slope direction. Ripple marks, for example, with crests normal to the current, are closely related to both convolute bedding and flame structures, and can accordingly be expected to have similar normal orientations. Additional work at Santa Paula Creek and elsewhere will be necessary to discriminate between analogous linear features formed either parallel or normal to the current or slope.

The irregularity and scatter of the fold axes in the disturbed layers seems compatible with an explanation involving current impact rather than with simple downslope sliding. With a slumping under gravity alone, where one layer is detached and free to glide upon the bed below, the assumption is usually made that fold axes are oriented normal to the dip of the paleoslope and parallel to the bed below. At Santa Paula Creek the plunges of fold axes into the bedding show that movement was not directly down the slope of deposition. If rupture of the bedding, detachment sliding, and folding has taken place under gravity alone, it seems more likely that the folds acquired an irregular orientation because the bedding when broken remained attached at one end but was folded with axes oriented obliquely at the other. At places, in addi tion, the folded layers were stretched and pinched and the broken ends of the axes were bent around to lie nearly parallel to the current or slope.

Another type of disturbed bed consists of deformed sandstone instead of mudstone layers and may no always be distinguishable from a bed with convolut lamination. Isoclinal and recumbent folds and sma thrusts, all in a single layer, show great shortenin and lateral translation. At 55 m a sandstone bed be tween 15 and 20 cm thick consists of at least fou subunits, the upper two of which are deformed int tightly compressed folds with an aspect suggestin "sealing wax or flow structure" (Fairbridge, 194 figure 1). The axial surfaces of the overturned an recumbent folds, which display considerable thicker ing and thinning, are inclined to the east. The zon of deformation are separated from undeformed sub units both above and below by planes parallel to th bedding along which there has been lateral transla tion. Apparently small folds of sandstone have forme within a slurry with décollement along slip plane above and below. They are the only structures note where the deformation, as judged from the nature c the upper contact, has followed deposition of the in mediately overlying subunit. The thinness of the zor

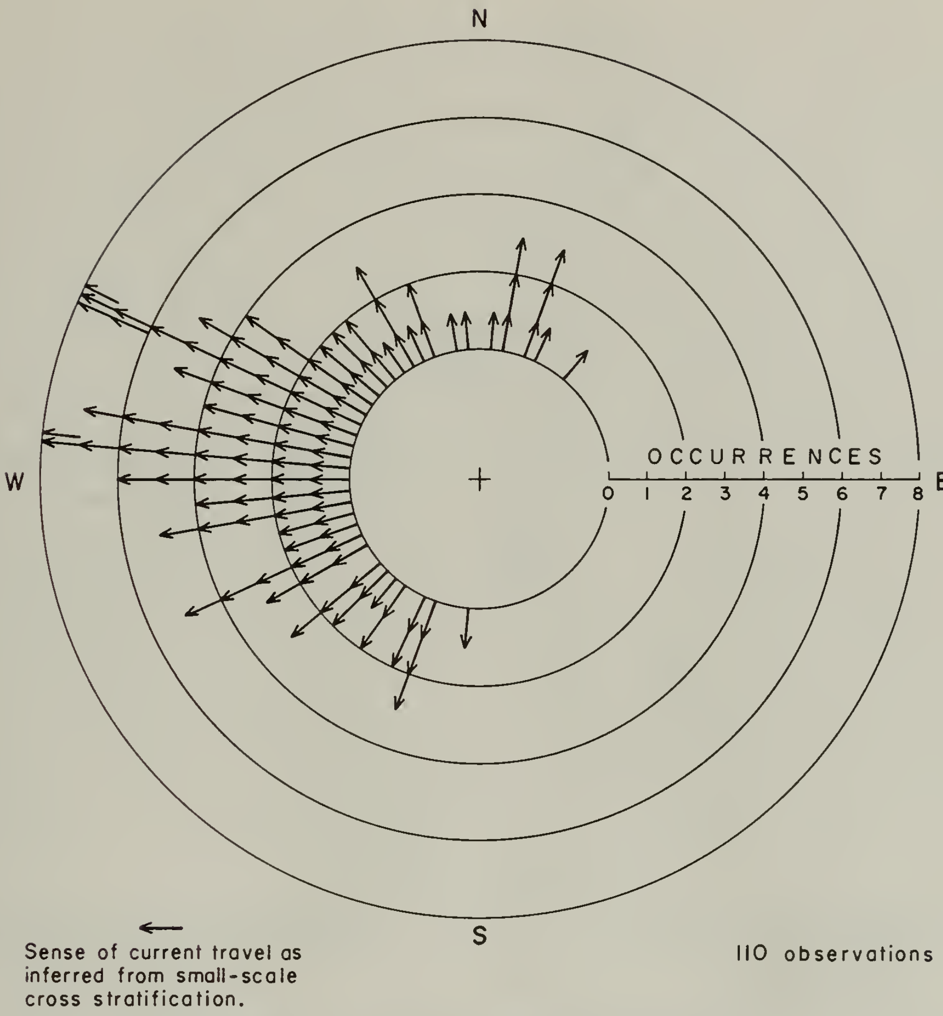


Figure 18. Current senses from small-scale cross-stratification.

olved, and the interpretation that the folding has en place in a quasi-liquid or slurried matrix, sug- ts that the deformation occurred after only a few ıtimeters of overlying sediment were laid down. fact, slippage may have occurred immediately fol- ving the growth of convolute lamination, for on west this layer grades into one with lamination. e deformation again appears to be related to the placement of the next sand layer.

similar origin is suggested to explain features such those illustrated in figure 16A. When the upper dstone layer was deposited, with wavelike load ms and some scouring at its base, the underlying or 30 cm of layered sand and mud was disturbed l moved laterally. Prolapsed bedding at other places v have formed in the same way.

everal layers of pebbly mudstone occur in the ta Paula Creek section, including one previously described (Crowell, 1957, p. 998). At 118.5 m bent slabs of mudstone up to 40 cm long with diffuse borders lie in a mudstone matrix with dispersed clusters of pebbles and rare cobbles. These associations require a mixing process where mudstone, sandstone, and conglomerate have been churned into a slurry derived largely from underlying mud. In fact, no observations have come from this re-study which require modification of the explanation advanced for their origin by Crowell. At one locality near 151 m pebbles and cobbles lie dispersed along a bedding plane (figure 17C). It seems likely that they were scattered as a strong current passed by and that all finer-grained fractions were deposited elsewhere and out of view. Such occurrences in other areas may be very difficult to distinguish from those resulting from rafting, including ice rafting.

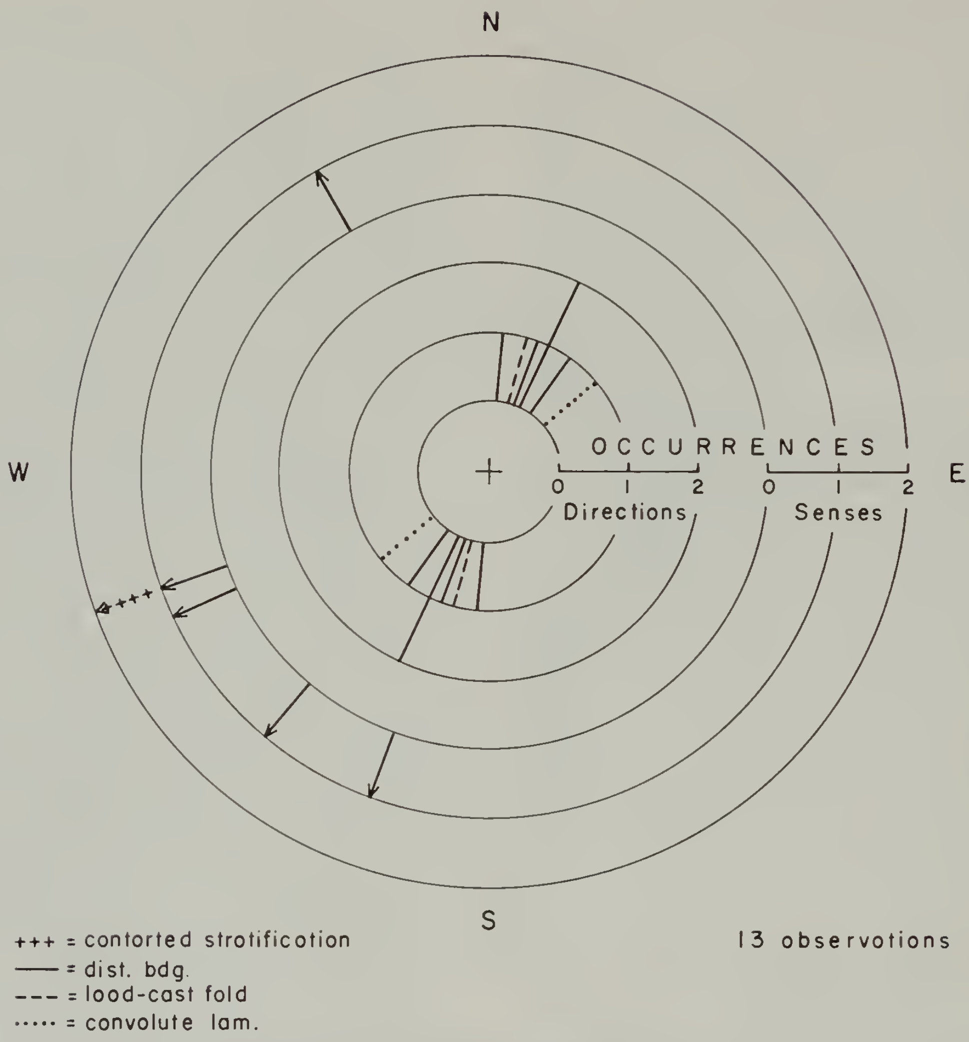


Figure 19. Orientations of varieties of contorted stratification. Structures giving senses shown with arrowheads in outer circles; those with directions only without arrowheads in inner circles. The orientations are shown as normals to the trends of axes. Senses are obtained from the sense of overturning or inclination of the axial surfaces.

Fossils With Preferred Orientation

A distinctive layer of *Macoma* (?) sp. and *Semele* (?) sp. shells lies 5 cm above the base of a 23-cm thick sandstone bed with faint lamination at 43 m (figure 17D) and which was laid down with a current from east to west (left to right). The pelecypod shells, which average about 2 cm in greatest diameter, are arranged in a layer with valves disarticulated but nearly touching and with concave sides upward. Most are tilted and imbricated with an inclination up to 30 degrees downward to the east into the inferred current. Their position apparently reflects a frozen instant in their transportation and not a position of stability at rest on the sea floor with their concave sides upward (Sorby, 1908, p. 189; Shrock, 1948, p. 316). Here it
seems that the shells have been carried in traction fro
east to west but concomitantly with settling so th
the convex side of the shell, pointing downward ar
forward, has offered the least resistance to lateral sli
ing. Transportation in a fluid sediment was alo
planes which are now preserved as faint laminatio
in the sandstone. This stage of transportation presu
ably took place with waning velocity penecontemp
raneously with deposition; the concave-upward po
tion may partly reflect the downward settling in t
waning current.

Several layers near 200 m show a distinctive pr
ferred orientation of the same shell types, but wi
the concave sides downward instead of upwards (fi
ure 17E). These shells are contained in distinctly lar
nated sandstone and appear to have acquired a re

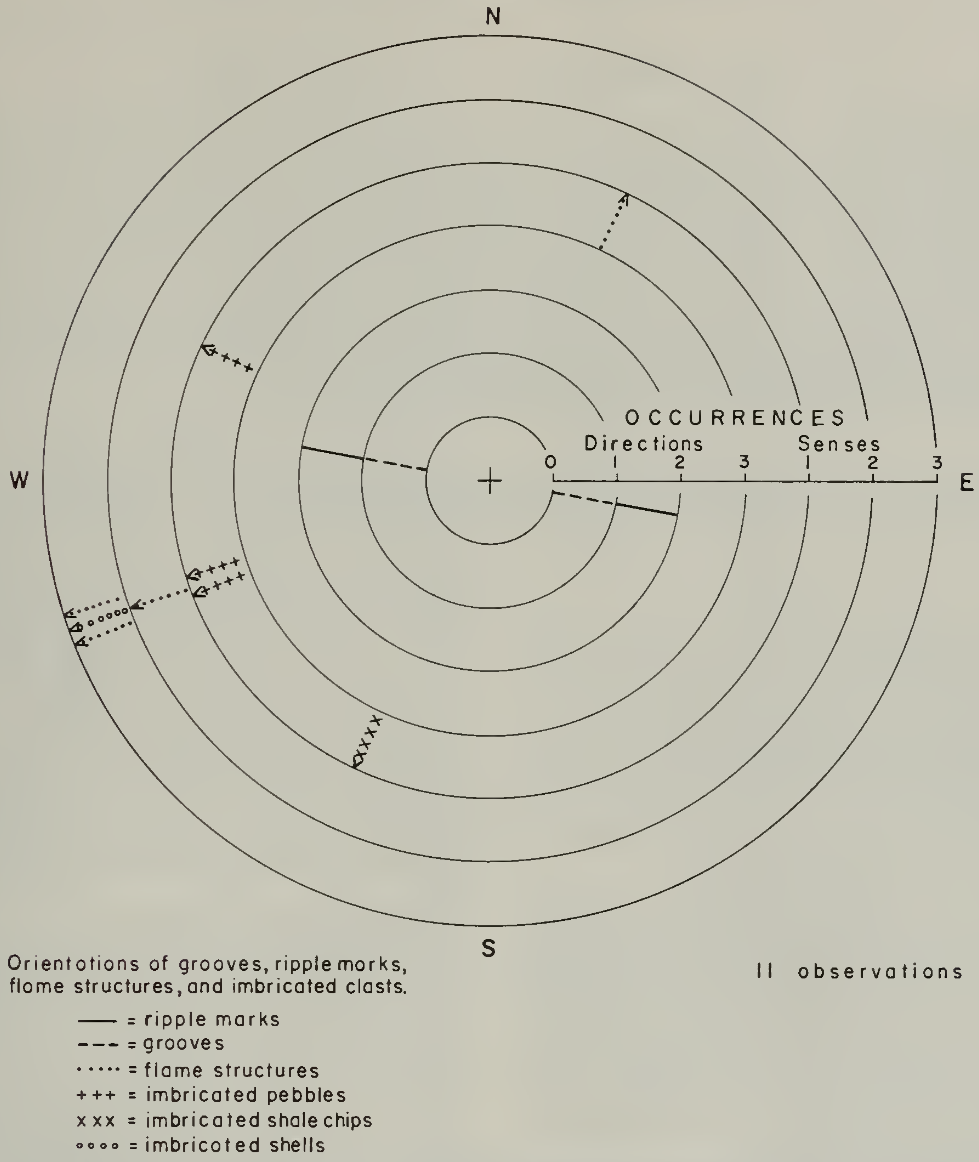


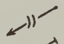
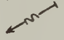
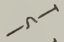
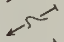
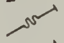
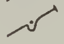
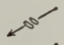
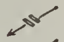
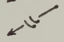
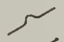
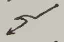
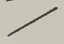
Figure 20. Orientations of grooves, ripple marks, flame structures, and imbricated clasts. The directions for grooves and the normals to the strike of ripple marks are plotted in the inner circles. Senses of flame structures and imbrications, in the direction of inferred travel, are plotted in the outer circles.

stable position which offers the least resistance urrents. Elsewhere similar fossils occur in thin s as a jumbled and broken coquina without con- ious orientation. Such concentrations of shell de- have been gathered into shallow depressions pre- bly by local weak currents.

DIRECTIONAL MEASUREMENTS

asurements of sedimentary structures which pre- bly reveal the direction of paleocurrents or the of the bottom are summarized in table 3 and s 18, 19 and 20, and listed in detail in table 4. ost cases the inferred current direction was first ured and then note made of the sense of movement along this direction. In the field the pitch (or rake) of the direction was recorded and the pre-tilting direction found by rotating this line around the strike line into the horizontal. Regional tectonic plunges in the region are less than 5° so the error introduced by ignoring plunges is less than 3°42″ (Norman, 1960, table 1). Most measurements are considered to be accurate to ±10°, but some, like flame structures and imbrications are much less precise although still useful. The reliability was much increased by the softness of the rocks because individual structures, such as small-scale cross-stratification, could be dissected in the field. Data recorded in the table come from single beds and in most cases these were verified by several observa-

Table 3.

Type	Number measured	Symbol on Figures 3 and 4
Small-scale cross-stratification	110	
Contorted stratification	1	
Disturbed bedding		
Direction only	5	
Sense of direction	5	
Convolute lamination	1	
Fold axes parallel to load cast	1	
Imbricated clasts		
Pebbles	3	
Shale chips	1	
Shells	1	
Ripple marks	1	
Flame structures	4	
Grooves	1	
Total:	134	

tions along the same bed; there is only one observation recorded per bed. In the current roses (figures 18, 19 and 20) all measurements having a sense as well as a direction are plotted with an arrowhead. Those without a sense are plotted as a line only and appear on both sides of the rose.

Summary and Discussion

This re-study of the beds at Santa Paula Creek draws attention to several features that require comment and interpretation and which bear on the manner of origin. To begin with, based on faunal and geologic considerations, we have concluded that sedimentation took place in upper bathyal marine waters greater than 270 m deep, in an environment relatively tranquil except during times of sand incursion.

The evenness and persistence of bedding suggests that the site represents part of the true floor of the Pliocene basin where the bulk of the sediments accumulated and includes mud as well as sand and rare coarser material. This inference is suggested as well by the similar character of the Pico Formation for many miles both east and west of Santa Paula Creek. Although the structures preserved within the beds prove transportation of sediment laterally, on the whole the processes were largely waning in competence so that processes of deposition predominated over those of transportation. We conclude from this evenness of bedding and the persistence of signature details that there was very little slope at the site of the Santa Paula Creek section and that the sedimentation surface was essentially flat, very much like it is today in the offshore basins of southern California (Gorsline and Emery, 1959; Emery, 1960, p. 53). At most there may have been a very gentle slope dow a broad submarine fan from an apex near the mou of a submarine canyon.

Sedimentation has clearly been episodic, for th section consists of sandstone layers, recording one s of sedimentation conditions, and mudstone layers, r cording another. The sandstone layers are the produ of relatively vigorous currents and were no doubt la down during a short interval. The rusty mudstones, o the other hand, may have accumulated over very muc longer time spans. Paraconformities and diastems su gest unknown durations when no deposition too place.

Sandstone layers display evidence of traction ar vigorous but fluctuating currents. Small-scale cros stratification, imbricated clasts, flame structures, ar convolute lamination all reveal a movement sens Ubiquitous parallel laminations within beds, bot graded and ungraded, attest to movement of one i ternal layer over another. These features are inte preted as the result of traction in which stresses fro a current are transmitted downward by the sliding layer upon layer during transportation and before fin deposition. Transportation has been by *viscous flu flow* (Dott, 1963, p. 112), in which the current ar sediment probably moved in pulses, now quickly, no a bit more slowly, and fluctuated as well from side side.

Graded beds are common at Santa Paula Creek b most beds show grading in association with or supe posed upon other structures, and ideal grading witho lamination and without small-scale cross-stratificati at the top is rare. Two possible explanations come mind. One, a current deposited an ideal graded b as the first distinct phase of deposition which w followed by a distinct second phase involving late traction of bed load. Two, the grading and the la inations were formed simultaneously as the curre decelerated and commenced deposition. The seco and preferred explanation seems more in accord wi what is known of sedimentation processes in flum and observable environments.

The evenness and persistence of thin beds, whi retain the same signature characteristics of litholog texture, and structure across the width of exposu require a sensitive balance between the paramet involving transportation and sedimentation. Ev where beds are disturbed, depressions in the disturb surface were immediately infilled and the sedimen tion surface smoothed. It seems that the currents clu to the bottom, in adjustment with the sedimentati surface, and always smoothed and restored and ma tained the evenness of this surface. If, as the result one depositional episode, the surface bulged a bit t

1	2	3	4	5	6	7	8	9
Obser-vation	**Location** Stratigraphic thickness from base of section measured, and side of creek where observation made: E = east side; W = west side	**Strike and dip of bedding**[a]	**Pitch or rake of directional structure** In degrees and marked **up** (U) or **down** (D) and/or **east** (E) or **west** (W)	**Estimated exactness** (Degrees ±)	**Quality of observation as a directional indicator**[b]	**Bearings of inferred currents or movements**		**Type of sedimentary structure**
						Direction only[c]	**Sense** (Sense of travel recorded)[d]	
1	33.2 W	70-72 S	00 W	30	F		250	Imbricated pebbles at base of graded bed
2	33.8 W		00 W	45	F		250	Flame structure
3	34.2 W		45 DW	30	F		205	Imbricated shale clasts
4	34.3 W		00 W	45	F		250	Flame structure
5	36.2 W		45 UW	45	P		295	Imbricated pebbles at base of graded bed
6	37.1 W		20 UW	10	G		270	Small-scale cross-stratification
7	37.6 W		00 W	10	G		250	Small-scale cross-stratification
8	40.9 E		00 W	45	G		250	Imbricated pebbles in graded bed
9	41.8 W		15 UW	10	G		265	Small-scale cross-stratification
10	41.9 W		10 DW	10	G		240	Small-scale cross-stratification
11	42.0 W	70-71 S	10 DW	10	G		240	Small-scale cross-stratification
12	42.1 W		10 DW	10	G		240	Small-scale cross-stratification
13	42.15 W	70-70 S	65 DW	10	G		185	Small-scale cross-stratification
14	42.2 W		10 UW	10	G		260	Small-scale cross-stratification
15	42.3 W		00 W	30	G		250	Imbricated shells
16	43.2 W		20 UW	10	G		270	Small-scale cross-stratification
17	44.2 W		25 DW	10	G		225	Small-scale cross-stratification
18	44.9 W		75 UE	10	P		355	Small-scale cross-stratification
19	46.1 W		20 UW	10	G		270	Small-scale cross-stratification
20	48.2 E		00 W	25	G		250	Small-scale cross-stratification
21	47.9 E		20 UW	10	G		270	Small-scale cross-stratification
22	48.9 E		20 UW	10	G		270	Small-scale cross-stratification
23	49.3 E		80 UW	10	G		330	Small-scale cross-stratification
24	49.4 E		20 UW	10	G		270	Small-scale cross-stratification
25	49.8 E		25 UW	10	G		275	Small-scale cross-stratification
26	50.0 E		50 UW	10	F		300	Small-scale cross-stratification
27	50.7 E	70-70 S	30 DE & UW	15	F	100		Grooves
28	52.0 E		30 UW	10	G		280	Small-scale cross-stratification
29	54.0 E		20 UE & DW	20	G	50		Convolute anticline[e] and ripple marks
30	56.4 E	70-68 S	60 UE	10	G		10	Small-scale cross-stratification
31	56.9 E		45 UE	10	G		25	Small-scale cross-stratification
32	57.2 E		45 UW	10	G		295	Small-scale cross-stratification
33	58.4 E		50 UE	10	G		20	Small-scale cross-stratification
34	59.3 E		35 UW	10	G		285	Small-scale cross-stratification
35	60.2 E		45 UW	10	G		295	Small-scale cross-stratification
36	61.6 E		90 U	10	F		340	Small-scale cross-stratification
37	63.0 E		00 E	40	P		70	Asymmetric folds of disturbed beds[e]
38	65.4 E		55 UE	15	P	15		Fold following load cast
39	68.2 E		45 DW	10	F		205	Small-scale cross-stratification
40	70.5 E		30 DW	10	G		220	Small-scale cross-stratification
41	71.9 E		35 UW	10	G		285	Small-scale cross-stratification
42	74.6 E		50 UW	10	F		300	Small-scale cross-stratification

1	2	3	4	5	6	7	8	9
Obser-vation	**Location** Stratigraphic thickness from base of section measured, and side of creek where observation made: E = east side; W = west side	**Strike and dip of bedding**[a]	**Pitch or rake of directional structure** In degrees and marked **up** (U) or **down** (D) and/or **east** (E) or **west** (W)	**Estimated exactness** (Degrees ±)	**Quality of observation as a directional indicator**[b]	**Bearings of inferred currents or movements**		**Type of sedimentary structure**
						Direction only[c]	**Sense** (Sense of travel recorded)[d]	
43	75.1 E		50 UE	10	F		20	Small-scale cross-stratification
44	76.0 E		30 UW	30	F		280	Small-scale cross-stratification
45	76.1 E		30 UE	10	F		40	Small-scale cross-stratification
46	76.5 E		45 DW	10	G		205	Small-scale cross-stratification
47	78.0 E		30 UW	10	G		280	Small-scale cross-stratification
48	78.1 E		80 UE	20	G		350	Small-scale cross-stratification
59	78.4 E		50 UW	10	G		300	Small-scale cross-stratification
50	78.6 E		50 UW	15	P		300	Small-scale cross-stratification
51	81.2 E	70-69 S	60 UE	10	G		10	Small-scale cross-stratification
52	82.7 E		45 UW	10	G		295	Small-scale cross-stratification
53	82.9 E		30 DW	10	G		220	Asymmetric folds of disturbed beds[e]
54	84.2 W		80 UW	15	G		330	Asymmetric folds of disturbed beds[e]
55	85.6 E		45 UW	15	G		295	Small-scale cross-stratification
56	85.7 E		45 UE	15	G		25	Flame structures
57	86.3 E		00 W	45	P		250	Flame structures
58	90.7 E		50 UW	30	P		300	Small-scale cross-stratification
59	90.8 E		10 UW	15	P		260	Small-scale cross-stratification
60	92.2 E		45 UW	10	G		295	Small-scale cross-stratification
61	92.8 E		30 UW	30	G		280	Small-scale cross-stratification
62	93.6 E		30 UW	10	G		280	Small-scale cross-stratification
63	94.5 E		10 UW	20	G		260	Small-scale cross-stratification
64	96.4 E	70-69 S	30 DE & UW	15	F	100		Ripple marks
65	96.9 E		45 UW	10	G		295	Small-scale cross-stratification
66	97.4 E		80 UW	10	G		330	Small-scale cross-stratification
67	98.7 E		60 UW	10	F		310	Small-scale cross-stratification with convolute lamination
68	100.5 E	69-71 S	30 UW	10	G		280	Small-scale cross-stratification
69	101.5 E		00 W	45	F		250	Asymmetric folds of contorted stratification[e]
70	103.4 E		80 UW	20	P		330	Small-scale cross-stratification
71	103.8 E		50 DW	10	F		200	Small-scale cross-stratification
72	105.0 E		30 UW	20	P		280	Small-scale cross-stratification
73	106.2 E		55 UW	10	F		305	Small-scale cross-stratification
74	106.9 E		45 UW	10	F		295	Small-scale cross-stratification
75	107.2 E		55 UW	10	F		305	Small-scale cross-stratification
76	107.6 E		45 UW	10	F		295	Small-scale cross-stratification
77	108.6 E		25 UW	10	F		275	Small-scale cross-stratification
78	108.8 E		35 UW	10	F		285	Small-scale cross-stratification
79	109.9 E		45 UW	10	F		290	Small-scale cross-stratification
80	110.6 E		45 UW	25	P		290	Small-scale cross-stratification
81	111.2 E		15 UW	10	G		260	Small-scale cross-stratification
82	111.6 E		15 UW	10	G		260	Small-scale cross-stratification

				10	G		340	Small-scale cross-stratification[f]
85	112.1 E		60 UE	10	G		10	Small-scale cross-stratification[f]
86	113.4 E		45 DW	10	G		200	Small-scale cross-stratification
87	114.0 E		30 UE & DW	10	F	35		Axes of folds of disturbed beds[e]
88	120.3 E	65-72 S	45 UW	10	P		290	Small-scale cross-stratification
89	135.2 E	65-75 S	30 DW	20	P		215	Small-scale cross-stratification
90	137.1 E		30 DW	20	F		215	Small-scale cross-stratification
91	142.0 E		30 UW	10	F		275	Small-scale cross-stratification
92	143.8 W	65-70 S	70 UW	20	F		315	Small-scale cross-stratification
93	147.8 W		65 UW	10	F		310	Small-scale cross-stratification
94	148.2 W		75 UW	10	F		320	Small-scale cross-stratification
95	150.2 W		45 UW	10	F		290	Small-scale cross-stratification
96	150.8 E		50 UW	10	F		295	Small-scale cross-stratification
97	153.2 E		20 UW	10	F		265	Small-scale cross-stratification
98	153.7 E		60 UE	10	F		05	Small-scale cross-stratification
99	155.5 E	65-70 S	00 W	45	P		245	Asymmetric folds of disturbed beds[e]
100	157.9 E	67-72 S	30 UW	10	G		275	Small-scale cross-stratification
101	158.0 E		30 UW	10	G		275	Small-scale cross-stratification
102	158.1 E		30 UW	10	G		275	Small-scale cross-stratification
103	161.5 E		15 DW	10	F		230	Small-scale cross-stratification
104	161.6 E		15 DW	10	F		230	Small-scale cross-stratification
105	162.1 E		40 UW	10	G		285	Small-scale cross-stratification
106	162.2 E		30 UW	10	G		275	Small-scale cross-stratification
107	165.2 E		00 W	45	P		245	Small-scale cross-stratification
108	170.0 E		50 UW	10	G		295	Small-scale cross-stratification
109	170.1 E		70 UW	10	G		315	Small-scale cross-stratification
110	170.2 E		60 UW	10	G		305	Small-scale cross-stratification
111	170.8 E		00 W	45	G		245	Small-scale cross-stratification
112	171.0 E		10 UW	10	G		255	Small-scale cross-stratification
113	171.8 E		20 UW	10	F		265	Small-scale cross-stratification
114	171.9 E		00 W	45	G		245	Small-scale cross-stratification
115	172.2 E	67-76 S	00 W	45	G		245	Small-scale cross-stratification
116	174.8 E		80 UW	15	G		320	Small-scale cross-stratification[g]
117	174.9 E		30 UW	15	G		275	Small-scale cross-stratification[g]
118	175.0 E		50 UW	15	F		295	Small-scale cross-stratification and convolute lamination
119	175.1 E		45 UE	10	F		20	Small-scale cross-stratification
120	175.7 E		45 DW	10	G		200	Small-scale cross-stratification
121	175.8 E		20 UW	10	G		265	Small-scale cross-stratification
122	176.6 E		30 UW	10	G		275	Small-scale cross-stratification
123	176.8 E	65-75 S	00 W	45	G		245	Small-scale cross-stratification
124	180.5 E		20 DW	10	G		225	Small-scale cross-stratification
125	181.0 E		45 UW	10	G		290	Small-scale cross-stratification
126	181.4 E		10 UW	10	G		255	Small-scale cross-stratification
127	186.2 E	63-75 S	45 DW	20	G		200	Asymmetric folds of disturbed beds[e]
128	199.5 W	66-78 S	80 UW	10	G		325	Small-scale cross-stratification
129	206.5 W		15 DW	30	P		230	Small-scale cross-stratification
130	212.0 E	68-70 S	45 UE & DW	15	F	25		Fold axes of disturbed beds[e]
131	212.5 E	68-71 S	45 UE & DW	15	F	25		Fold axes of disturbed beds[e]
132	213.5 E		45 UE & DW	15	P	20		Fold axes of disturbed beds[e]
133	215.0 E		60 UW	10	G		305	Small-scale cross-stratification
134	215.5 E	65-72 S	60 UE & DW	30	F	05		Fold axes of disturbed beds[e]

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[a] Strike plotted as bearing angle between 0° and 179°.

[b] P = poor; F = fair; G = good.

[c] Direction plotted as bearing angle between 0° and 179°.

[d] Sense of travel plotted as bearing angle between 0° and 359°; and rounded to nearest 5°.

[e] Sense of assumed movement taken as normal to fold axes and in sense of overturning of axial surfaces. If folds not asymmetric, direction only plotted.

[f] Three observations within same bed, suggesting rotation of the current sense upward, in a clockwise sense.

[g] Two observations within same bed, suggesting rotation of the current sense upward, in a counterclockwise sense.

high, the next influx of sand sought the flanking hollows.

Beds of similar thickness and character tend to be grouped together in the section. Assuming that bed thickness reflects the volume and strength of the emplacing current, it seems likely that the association of similar beds is a consequence of continuing balance between parameters of submarine topography and supply of sediment. Material, accumulating and stored at the basin margin, from time to time moved downslope and seaward. It may have slipped away violently or have flowed to the depositional site over a relatively long period. Factors such as distance from basin margin, the slope of the basin margin and basin floor, the nature of the sediment, and the integration and extent of the supply network largely determined the thickness and character of beds in the region of deposition. A group of beds of similar thickness must have accumulated during an interval when these conditions were approximately constant and in balance.

Inasmuch as basal contacts of many sandstone beds show minor erosion, some currents invaded the environment with sufficient energy to remove unconsolidated sediment and add it to the load in transportation even though these currents were waning in vigor so that deposition prevailed on the whole. Other currents deformed the substratum although differences in the properties of the substratum, as well as the competency of the current, may have regulated the aspect of the resulting layer. It may be that buried beds and lenses of porous sand in the upper few meters of the floor were quicksands and when shocked by current impact, lost porosity. Upward squirting pore-water may thus have ruptured the containing mud layers, and aided in fragmentation and the inception of deformed bedding. Such shock as well may have forced thixotropic clays across the gel-sol transformation, contributing to a sharp weakening in strength (Boswell, 1961, p. 43–51; Crowell, 1957, p. 1005; Dott, 1963, p. 107).

Disturbed beds, which are here interpreted as the result of current impact, display axes which are approximately parallel to the current directions (figures 18 and 19). In fact, we detect little evidence in support of the hypothesis that the axes have been oriented parallel to contours of a paleoslope. Our interpretation therefore differs diametrically from that of Murphy and Schlanger (1962) who placed great reliance on fold axes of "slump" structures as slope indicators and accordingly interpreted other directional structures as products of currents moving parallel to the slope.

The currents responsible for small-scale cross-stratification, imbrications, and flame structures in the main have flowed toward the west with extreme senses toward the south and toward the northeast (figures 1 and 20). In the field no significant variation in lithology was noted which might be related to differin sources of sediment supply. The variation in directio is interpreted largely as reflecting the meandering o currents as they moved along the bottom rather tha as the result of distinctly different sources, althoug more than one source probably contributed. In addition, their direction may have been partly controlle by their initial momentum taken when they reache the flat basin floor after dropping down a steep basi margin. The west-flowing general direction is nearl parallel to the strike of major Pliocene structural features in the region so that filling of this basin or troug also seems to have been primarily by longitudinal sedimentation (Kuenen, 1957).

Although the contrast between layers of sandston and layers of mudstone is of first-order conspicuousness at Santa Paula Creek, internal stratification o lamination is common. Beds display interior difference in texture, structure, and lithology, such as grading cross-stratification, and lamination. In general thes variations are gradational and contacts between bed are sharper than those between internal variations. I reconstructing the sedimentation history responsibl for the strata it is useful to recall the sedimentatio unit as defined by Otto (1938, p. 575): "that thicknes of sediment which was deposited under essentiall constant physical conditions." For the sandstone laye at Santa Paula Creek, however, which are commonl laminated at their base and with small-scale cross-stratification at their top, and with grading superpose throughout, the physical conditions during depositio have obviously differed. It therefore appears desirab to separate in concept the useful notion of a basi stratigraphic unit (the bed), which can be define satisfactorily in the field, from the sedimentation eve or events responsible for its deposition.

Where a bed is subdivided into subunits, such as b lamination, close agreement can usually be reache between different observers on the definition of the descriptive boundaries, but observers may disagree th the subunits are the result of distinctly different phys cal processes. Some may envisage a single deposition event with minor fluctuations, or subevents, where others may feel that sound interpretation demands di tinctly different sedimentation events.

Thick mudstone beds, for example, succeed thi sandstones. Most of the mudstone, which is da brownish-gray, displays grading, sand lenses, ve small-scale cross-stratification, and isolated sand grai features which are most easily accounted for by cu rent origin. In figure 17E a mudstone bed is portray in which oriented shells attest to current depositio

indeed currents deposited these muds, the tendency
r thick mudstones to succeed thick sandstones is
adily explained and the contrasting muddy layer
ay have followed directly from the same process
at deposited the sandy layer. A current with a large
lume of sand perhaps also contained a large fraction
mud, but this finer material lagged and settled more
wly than the sand, and formed a layer overlying
e first-deposited sand. Because many mudstone beds
e not underlain by sandstone, however, some cur-
nts either did not transport or deposit sand, or did
laterally beyond the extent of the exposures studied.
ner material thrown into suspension perhaps ex-
nded and settled beyond the margins of sand depo-
ion to form the dark mudstone.

The bulk proportion of mud and sand in these
vers is probably about the same as the proportion
oded from land and transported to the sea, but per-
nial questions arise concerning the likely processes
at carry the sediment seaward from the shore to
e basin floor. Observations at the heads of active
bmarine canyons indicate that large amounts of sand
but very little mud—are carried into them by long-
ore drift. The sand accumulates in canyon heads
d then intermittently or more or less continuously
oves down the canyon. Mud, on the other hand, does
t gather in active canyon heads in large quantity.
is apparently kept in suspension by vigorous near-
ore currents and only accumulates temporarily in
atively tranquil areas beyond the surf zone. Mud
at settles for a time on a shelf area to either side of
bmarine canyons may be swept laterally by various
rrents and perhaps trapped along reaches of sub-
rine canyons at considerable distances down from
ir heads. This mud, perhaps mixed with sand, gravel,
d organic debris that has moved along the canyon
ttom from the head, may at intervals move farther
wn the canyon and out upon the basin floor as an
derflow. In fact, this mixing of sand and mud may
a requirement for a true turbidity current, and
h currents may therefore originate at positions
thin canyons well down from their heads.

On the other hand, there is a lithologic distinction
ween mudstones referred to above and presumably
l down by underflows, and the rusty weathering
s. The latter are very minutely laminated, rich in
aminifera, and with extreme uniformity and per-
ience. These characteristics suggest that they are
ly pelagic deposits, resulting from slow settling of
pended sediment. Between times when bottom cur-
ts brought in sediment, debris may have settled
m overflows or plumes of muddy water that ex-
ded seaward on the surface from rivers in flood.
olian and biogenic debris, with some material from
interflows, perhaps contributed as well. Presumably a long and tranquil interval is implied by a thick rusty-weathering mudstone layer, during which the more or less continual "rain" of fine-grained sediment was not interrupted. The time lapse between invading bottom currents is therefore related to the thickness of rusty mudstone. This period may be related to the time required for accumulation of a critical quantity of sediment in regions closer to shore before it moved basinward, or to intervals when the locale was sheltered from currents which for a time were depositing sheets of sediment somewhere else.

With the picture emerging of a broad and deep trough of deposition with a nearly flat floor, the control for sedimentation came from the interplay between tectonics and gross topography, the nature of transporting agents, local environmental influences at the site of deposition, and the nature of the sediment source-area. Clearly the tectonic framework set the stage primarily for the type of sedimentation at Santa Paula Creek, and was responsible for the shape, size, and depth of the basin, for the steepness of the margins, and for the ruggedness, size, and pattern of streams in the ultimate source area on land. Through similar control the tectonics determined the orientation and shape of the coastline which in turn influenced the direction and strength of longshore drift, the location and size of the areas of beach-sediment accumulation, and the positioning of submarine canyons (Crowell, 1952). Details observable in a sample of the sediments from the basin floor, such as the strata studied at Santa Paula Creek, display the imprint primarily of sedimentation and transporting processes, but set within this gross environment. Bottom-seeking currents, spreading out over the flat floor in cuneate, spatulate, or pinnate tongues apparently follow shallow paths across the floor. These paths are perhaps at the margins of previously deposited lobes of sand, which, upon deposition, stand higher in barely perceptible relief. After several layers are deposited along one broad course, later currents swing to one side and deposit a series of layers in a quite new position. Sedimentation through time seeks to maintain a flat and even floor as the basin fills.

Several processes operate to complicate this simple pattern of basin filling. Threads of currents moving down channels appear to build up pinnate tongues of sediment, thick and coarser within channel ways, with low levees on the sides, and local extensions laterally (Menard, 1955; Bates, 1953, p. 2128). Differential compaction within the upper meters of section may result in low depressions which, in turn, guide new currents. Data suggesting that deposition is in elongate lobes have been assembled for the Pico Formation some miles to the east by Winterer and Durham (1962). In addition, "jet" theory applied to underflow (hyperpyncnal flow) suggests such a shape and a velocity distribution so that deposition will be inhibited along the axis of the flow and more dominant in broad areas to either side (Bates, 1953, p. 2123). At Santa Paula Creek, the beds are cut primarily in a direction parallel to the emplacing currents which may in part account for the striking evenness and persistence of bedding and signature characteristics across exposures. The control for the second-order features observable in the strata therefore comes from the nature of the sedimentation agents, from the character of the sediment contributed to the environment, from position with respect to submarine canyons, and from factors in the local environment, such as compaction and thixotropy, which influence the depositing current.

It seems clear that the currents at Santa Paula Creek were *bottom-seeking currents* that did not roil the waters all the way to the surface but in a layer of unknown thickness relatively near the ocean floor. They also moved across a nearly flat basin floor where the slope may have been nearly imperceptible. Were they truly turbidity currents, or were they bottom-hugging underflows? Abrupt variations within a single bed are not easily reconciled with the concept of a turbidity current as a homogeneous cloud of suspended sediment moving rapidly down-slope and governed chiefly by density differences. Instead, from our description emerges a picture of an underflow current with ill-understood complexity. We imagine an intricate and turbid current system which produced complex sorting in all three directions within the moving mass. Moreover, the sorting mechanisms which operated within the current were at times obscured by the ability of the current to add sediment through erosion. Although the average velocity of the current must have diminished, so that deposition on the whole prevailed, fluctuations in speed and direction of filaments within the moving and turbulent mass were considerable. Penultimate transfer of energy to the transient bed load apparently imposed laminations on graded layers and the complex underflow possessed sufficient energy to move a bed load by traction.

These *high-energy underflows* were associated with or succeeded by pulses or currents which produced slightly different results. Upper layers of many sandstone beds display tiers of small-scale cross-stratification which indicate that the current continued to flow after the principal load had been laid down. It seems likely that the density of the turbulent mass could only be maintained if there were a large portion of mud as well as very fine sand within it. Finally, as the turbulence and the average velocity of the current diminished, laminated dark mud with exotic san grains was deposited. The concept of a dilute ta (Kuenen, 1953b, p. 1050) accordingly seems attractiv as a logical way to explain this sequence. On the othe hand, the variability of current directions at Sant Paula Creek suggests that lateral threads of the curren might account for some of these features. Weak evanescent filaments, reaching out from the main spatulat mass of the underflow, perhaps deposited the dar mudstone.

CONCLUSIONS

We therefore conclude that the sandstone beds a Santa Paula Creek were laid down by high-energ underflows of great complexity and variability. A relatively thin layer of roiling water and sediment move down the steep margins of the basin, or out from th mouth of a submarine canyon, and across the flat floo of the basin. The turbulent tongue perhaps flowed a a continuum for a relatively long period, or perhap ephemerally, and as a density underflow beneath th ocean water and across the sedimentation surface. Energy acquired in flowing down the basin margin wa sufficient to carry it across a flat floor. Vigorous currents possessed surplus energy or capacity to erod the bottom, to drag parts of the floor up into it, an to deform layers previously deposited.

Waning currents carrying fine sand and mud produced small-scale cross-stratification, winnowing mu during flow, and finally deposited laminated dark mu alone. Laminated red-weathering mud, on the oth hand, appears to have settled slowly from pelagi debris, perhaps largely brought to the basin by ove flows of muddy river water.

It appears useful to return to the concept of vertic position of flow in a basin: to the concept of *overflo* *interflow*, and *underflow*. At any of these positio turbulent flow may vastly predominate in any o current over laminar flow, and the bulk-density co trast necessary for flow under gravity maintained b turbulence. Such a current is perhaps a turbidity cu rent but considerable turbulence is almost always pre ent in fluid flow. Laminar flow, in contrast, althoug perhaps common locally within all currents, will lea a direct record if in an underflow, where, for exampl the final stages of motion of bedload result in the sli ing of layer on layer producing laminations. Su structures are credited by some to *traction curren* implying a distinctly different mode of transport fro turbidity currents (Packham, 1954, p. 466) and b others to a "traction carpet" at the base of a turbidi current (Sanders, 1963, p. 177). Most directional-cu rent structures displayed in beds are produced b

derflows, considered here as a more inclusive variety
flow than turbidity current on one hand and trac-
n current on the other. These two types are pic-
red as species of the genus underflow although most
rkers today apparently conceive of turbidity cur-
nt and underflow as synonyms. The distinction be-
een the two seems further desirable, at places like
nta Paula Creek, in order to avoid the concept of a
bidity current, implying turbid flow, with a trac-
n current at its base. We suspect that the wide
ceptance of the turbidity-current concept hinges on
fact that it explains the emplacement of coarse
iments into deep basins but it is actually the aspect
underflow that is critical in this explanation. To us,
urbidity current is an underflow in which muddy
iment contributes through turbulence to maintain-
the bulk density necessary for flow.

The same principles of flow of course apply to turbidity currents as to all currents. Under circumstances where there is great turbulence, a thorough mixture of grain sizes, including mud, and a rapid loss of energy downflow with deposition, ideal graded bedding without interspersed lamination may be produced. Such underflows represent one end of a gradational series and can perhaps be termed an ideal turbidity current. From this extreme we picture a gradational series through all intermediate types of underflows to the other extreme, that of an ordinary stream. A stream on land is an underflow of mixed turbulent water and sediment, flowing beneath the fluid air, and is an example of a traction current. We therefore conclude that the beds at Santa Paula Creek were primarily laid down by underflows and that most were deposited by turbidity currents in the sense intended by Natland and Kuenen (1951).

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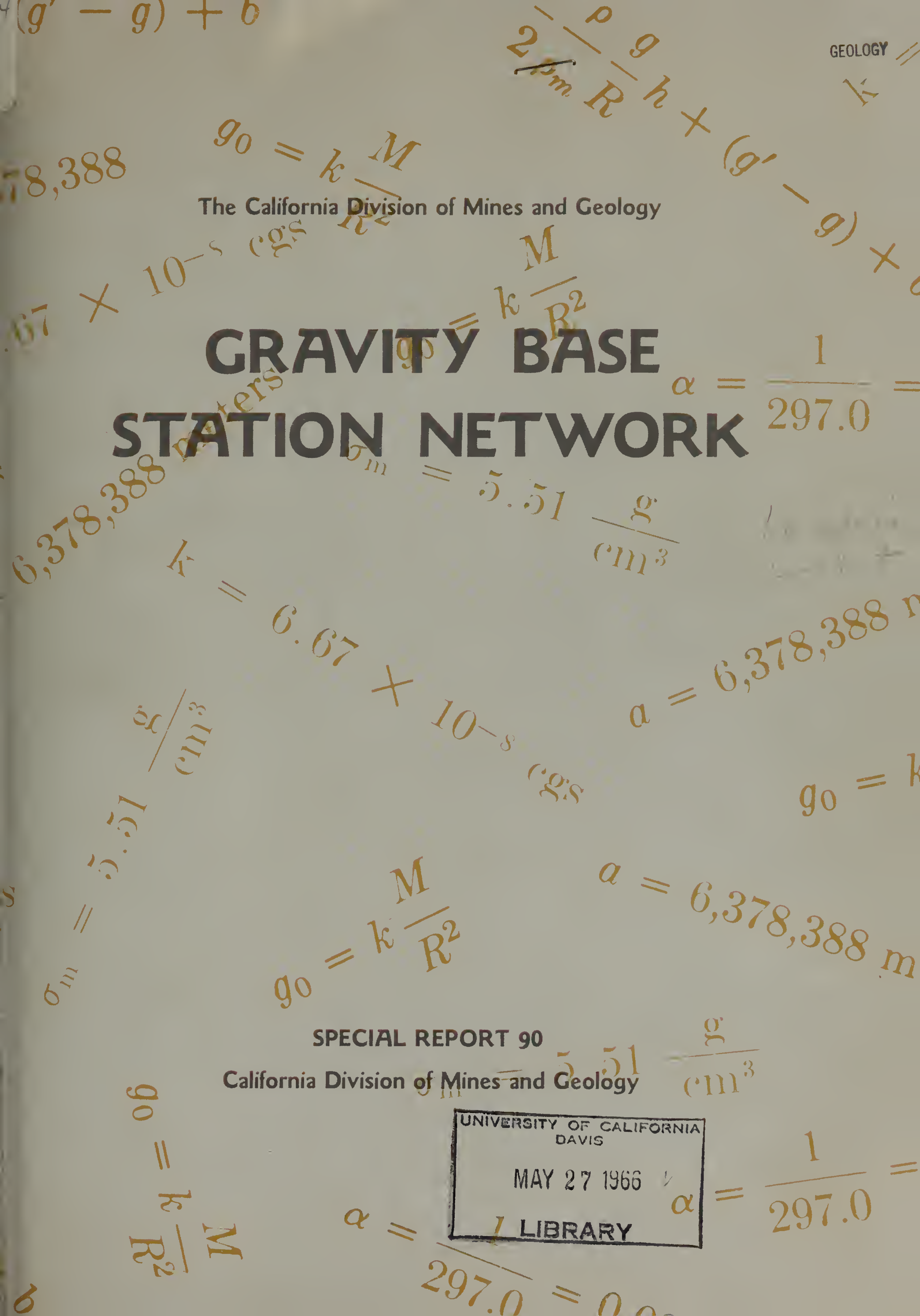
$g_0 = k\frac{M}{R^2}$
$k = 6.67 \times 10^{-8}$ cgs
$\sigma_m = 5.51 \frac{g}{cm^3}$
$a = 6,378,388$ m
$\alpha = \frac{1}{297.0}$

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